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ELECTROMAGNETIC PULSE EFFECT ON CIVILIAN FACILITIES

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This paper describes the effects of nuclear electromagnetic pulse on the civil sector. In particular it focuses on the vulnerability of electropower systems, which was one of my major interests while working at Lawrence Livermore National Laboratory.

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PREFACE

The Office of Energy Storage and Distribution of the U.S. Department of Energy has formulated a research and development program for the assessment and protection of electric power systems when subjected to nuclear electromagnetic pulses (EMPs). This program addresses a problem which is an international concern, and unclassified information is being shared among the United States, West Germany, the United Kingdom, France, Switzerland, and Sweden. The exchange of information and assistance on special problems reduces the cost of the research activities among the nations.

A preliminary assessment of a major electric utility company is presently being conducted under the U.S. program. High voltage pulse injection experiments on transmission and distribution components are being performed to determine the strength of this equipment to steep-front short-duration surges to develop a data base for the assessment. In the event that protection is needed to enhance the reliability of electric power, a major challenge will be to find solutions to the protection problem that are are affordable and will solve other related problems that are a concern to the electric utility industry. Otherwise, the solutions will not be implemented except for specialized military applications.

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FIGURES

1. INTRODUCTION

BACKGROUND

From the early days of work on nuclear explosives, scientists have been aware of a variety of weapons effects that go well beyond those of conventional explosive weapons both in the range of mechanisms that are involved (e.g., alpha, beta, and gamma radiations, heat pulse, and shock waves) as well as in the awesome magnitude of the effects.[1,2] The early detonations of nuclear weapons were all at or near the earth's surface, where many of the effects that accompany nuclear explosions were dissipated within a few kilometers of ground zero. Thus early attention focused on the offensive use of such weapons and on the various mechanisms whereby damage could be inflicted on the intended target. Nuclear detonations outside the dense, lower atmosphere did not have a high priority, although theoretical predictions had indicated that such events would cause interactions with the electrons in the ionosphere with resulting strong local perturbations in the electric field.

But this lack of attention did not persist. On July 9, 1962, the United States conducted a high altitude nuclear test at the Johnston atoll area of the Pacific ocean. This test caused scientists to reassess the electromagnetic field effects of nuclear detonations, particularly those at altitudes of 25 miles or more. This high altitude nuclear explosion, which had the code name "Starfish," was conducted with a 1.4-megaton hydrogen bomb 248 miles above Johnston Island. This particular test had an impact on several types of electrical systems in the Hawaiian islands, about 850 miles from the location of the high altitude burst. For example, on Oahu there were a series of failures in street lighting caused by burned out fuse elements that were installed to protect the circuits from sudden current surges. In Honolulu, multiple burglar alarms were triggered, and circuit breakers were opened in a number of power lines. All this pointed to an effect that was much more widespread than had been contemplated and that had the potential to significantly disrupt both the civil sector and military systems. In addition, failures and malfunctions were observed in earth orbiting satellites, and radio transmissions were blacked out in several frequency bands, all of which pointed to potential problems for military systems of great importance to the deterrence posture.

Several years earlier, the designers of the first nuclear weapon had predicted the creation of electromagnetic fields by nuclear explosions, and early weapons tests used electromagnetic shielding techniques. In the late 1950s, the significance of the electromagnetic pulse (EMP) to military systems was recognized, and more attention began to be paid to exoatmospheric nuclear weapons effects and, in particular, to their impact on strategic systems. The first concern was about EMP coupling to the silos and buried cables of the Minuteman system.

Today vulnerability to EMP is even greater because of the widespread use of sophisticated and sensitive electronic devices both in military and civilian systems.

ELECTROMAGNETIC PULSE (EMP) EFFECT ON CIVILIAN SYSTEMS

In the event of an EMP being generated by a thermonuclear explosion, the overall effect would probably be a severe disruption of the civilian economy as a result of loss of power and the shutdown of a significant number of electronic and computer-controlled systems. Much of the transportation system would be disrupted. Banking and other financial networks would be affected, as well as communications, TV and radio broadcasting, telephone service, medical systems, certain water supplies, industrial plants, and other facilities. In economic terms, such an event would be a disaster.

Interest in civil systems is quite recent in comparison to interest in military systems; therefore it has not produced a large data base. Each individual system has its own features, strengths, and weaknesses, which can only be assessed by detailed evaluation. Much of what is available in terms of information about civil systems is extrapolated from what has been done in connection with the evaluation of military hardware and systems.

One study done in the civil sector was sponsored in the United States by the Federal Emergency Management Agency (FEMA), which has been involved in a program of electromagnetic pulse hardening of its facilities since 1970.[3] The FEMA facilities in a number of the regions have been surveyed for EMP susceptibility and have had protective measures installed on life support and radio communication systems. Many state and local emergency operation centers have been hardened against EMP, and a number of emergency broadcast systems have received EMP protection.

Telecommunications

The telecommunications system is a large and complex set of networks and subsystems. The technology employed is diverse, ranging from a simple pair of wires connecting individual instruments to the latest optical components for transmitting large numbers of messages. The trends are toward more use of advanced technologies, including microprocessor chips, computers, and high technology receivers and transmitters; therefore, without special engineering design, the EMP effects would be severe.

Transportation

The main components are automative, truck, and rail systems on land, barge and merchant ships on the sea, and commercial and private aircrafts in the air. These vary greatly in their susceptibility to EMP. For example, private autos until recently would have been relatively unaffected by EMP. Unfortunately, however, from the standpoint of EMP vulnerability, automative technology has been moving in the wrong direction by adopting new technologies such as microprocessors, sophisticated electronics, and other new materials. Trains could be inoperative after an EMP event because of damage to computer-aided control systems, and locomotives would be unable to operate without a power supply. Airplanes also would be greatly vulnerable.

Banking and General Business Activities

Banking institutions increasingly depend on a variety of services that facilitate transactions, record keeping, national and international exchange of funds, and the general efficiency of the banking business. The principal tool used in providing these services is the computer, which is usually connected to a network of other computers by internal cabling or external communication links. Both the computer and the communication links would be highly vulnerable to EMP induced effects. Industrial processes would also be seriously affected.

Electric Power Systems

The electric power system is another large and complex system. Its vulnerability to EMP effects will be analyzed in detail throughout this paper.

OBJECTIVES OF THE DOCUMENT

Recent studies have analyzed the potential effects of EMP on civilian systems. Among them, the most ambitious is the study of the interaction of EMP with electric power systems, including nuclear power plants. This paper focuses on this topic. The data and findings have been taken from the open literature (see the references and bibliography) and from private discussions with scientists directly or indirectly involved in these studies. Among them are:

- Randy Barnes at the Oak Ridge National Laboratory, Leader of the DOE NBB-033 research program (see Section 5).

- Hriar Cabayan at the Lawrence Livermore National Laboratory, a specialist on electromagnetic effects including EMP and high power microwave, one of the members of the EMP advisory group for the DOE research program.

- Frederick Tesche, Lu Tech Incorporated, a specialist on EMP effects, contractor for the DOE research program.

- Edward Vance at S.R.I. International, a contractor for the DOE research program, an EMP effects specialist.

- Carl Baum, Air Force Weapons Laboratory, an EMP effects scientist.

2. EMP THREATS

The detonation of a nuclear weapon is always accompanied by an electromagnetic pulse. Although the visible effects of an EMP on systems can be less dramatic than the destruction due to other nuclear effects such as blast or thermal radiation, it is widely acknowledged that EMP can cause significant upset, degradation, and permanent damage to electrical systems.[3,4] The extent of upset or damage depends on many factors such as weapon yield and burst location.

EMP GENERATION

The electromagnetic pulse is generated mainly by an intense pulse of prompt gamma rays, produced by a nuclear blast. The rise time of the gamma pulse is of the order of a few nanoseconds. The gammas move outward from the burst at the velocity of light. As the gammas travel through the air, they produce a flux of Compton electrons that constitute an electric current density (Compton current pulse) with rise time and velocity comparable to that of the gammas.

The Compton electron recoils somewhat like a struck billiard ball. As the recoil electrons move through the air or other material medium they loose energy to other atomic electrons and eventually are brought to rest within a distance known as the mean forward range. The mean forward range depends on the medium (a few meters in sea level air).

A spherically symmetric distribution of radial Compton current produces only spherically symmetric radial electric fields with no magnetic or radiated transverse fields. The radiated fields of EMP are the source of the threat under consideration. The radiated EMP is produced by the Compton current and by assymetries produced by the air-ground interface, the atmospheric density gradient, and the geomagnetic field through its deflection of the recoil electrons.

The geomagnetic field deflects the recoil electrons in directions other than the direction of the incident gammas. The Larmor radius of the recoil electrons in the geomagnetic field is of the order of 50 to 100 meters at sea level. In order for the geomagnetic field to be effective, the Larmor radius of the recoil electrons must be comparable to their mean forward range.

It is estimated that about 10^{-6} of the nuclear energy in the nuclear explosion goes into EMP. The location of the explosion is an important parameter in determining how far this energy is radiated. Two regions surrounding the nuclear blast are important in EMP considerations: the deposition region (source region) and the radiation region. The extent of these regions depends on the size and the height of the blast. The deposition region is the space near the burst where the EMP is generated. It contains a highly conductive plasma and intense electric and magnetic fields. The radiation region contains somewhat smaller fields and extends far beyond the deposition region. The electromagnetic field propagates radially away from the burst as a plane wave. The deposition region is an equivalent radiating antenna for the wave fields and has a far field range dependence of 1/R, with R being the radial distance from the burst. The electric field E and magnetic field H are related by $E = \eta x H$, where $\eta = 377$ ohms is the impedance of free space.

HIGH ALTITUDE EMP OR EXOATMOSPHERIC BURST EMP

Exoatmospheric bursts take place at altitudes higher than 40 km above the earth. HEMP refers to EMP produced on the surface of the earth and in the atmosphere below 40 km. The standard description is as follows. An intense burst of gamma rays in the energy range of one to a few Mev is emitted within a few tens of nanoseconds following the explosion of a nuclear weapon. For an exoatmospheric nuclear explosion, these gamma rays propagate in a thin spherical shell moving at the speed of light away from the burst. The gamma rays are not attenuated in space, since there is no matter to absorb or scatter them. When the downward directed rays encounter the upper regions of the atmosphere, around an altitude of 40 km, they begin to interact with the atoms of the atmosphere in substantial numbers. The dominant interaction process is Compton scattering, as shown in Figure 2-1, in which the gamma ray transfers part of its energy to an electron from an air atom, and a gamma ray of decreased energy is scattered in approximately the same direction that the gamma ray was traveling. Therefore, when the gamma ray shell intercepts the upper regions of the atmosphere, it can be thought of as being converted to a shell of very energetic Compton electrons traveling in approximately the same direction and speed as the primary gamma rays. However, unlike the gamma rays, the Compton electrons are charged particles and are turned coherently in

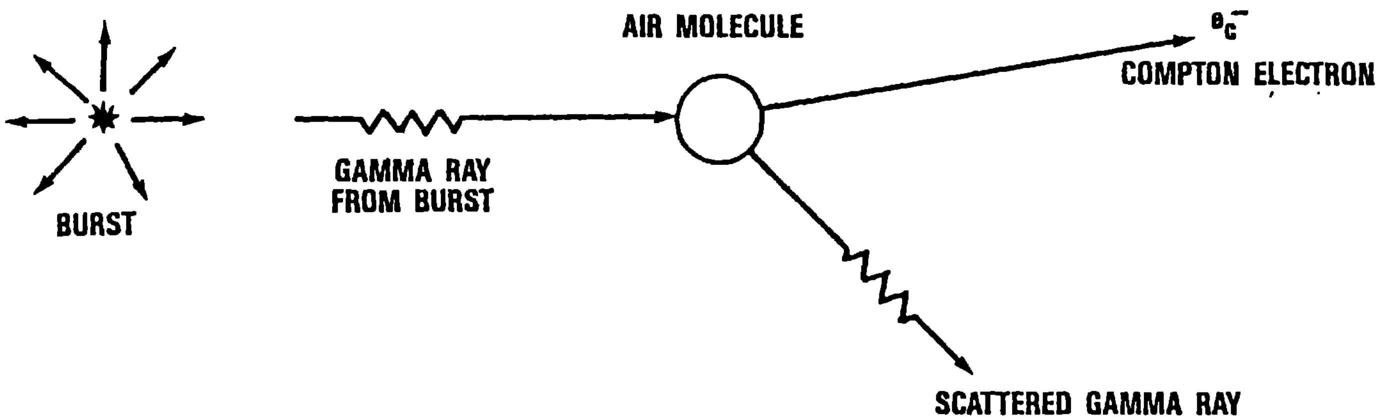


Figure 2-1. Creation of charged particles by a nuclear burst.

a transverse direction as they move through the magnetic field of the earth. This electron motion produces transverse currents which in turn give rise to a radiating electromagnetic field; the field continues to propagate through the atmosphere and to the surface of the ground as if contained in the same spherical shell that the gamma rays had orginally formed (Figure 2-2).

Another way of viewing the phenomenon is to consider the transverse motion of the Compton electrons to constitute a very large phased array antenna that covers the upper atmosphere in a spherical shell and propagates coherently in the same direction in which the gamma rays were traveling (Figure 2-3). The area of coverage for high altitude EMP is shown in Figure 2-4. The peak value of the electric field varies from 0 to E max in different areas, depending on their relative position with respect to the point directly under the blast (Figure 2-5).

The preceding description covers only the initial part of the HEMP process. The total process is a continuous succession of events that occur from within a few nanoseconds of the blast to several hundred seconds afterwards. Experts on EMP phenomenology have broken the process down into three time domains that can be treated separately: early time, intermediate time, and late time.

The early time HEMP arrives at the earth's surface very quickly and lasts one microsecond. It is caused by the first pulse of gamma rays released from the nuclear explosion. It has substantial energy content in the frequency range between one and several hundred megahertz.

The intermediate time HEMP occurs from 1 microsecond to 0.1 second and produces electric fields with frequency content between 1 and 10^5 Hz.

The late time HEMP concerns everything that happens after 0.1 second and includes the frequency below 1 Hz. Included in this is the magnetohydrodynamic EMP (MHD EMP) discussed next.

It is important to note that the HEMP process produces the high frequency content at the earliest time and the lower frequency content later in time. This is due to the nature of the nuclear sources produced by the device, with the highest frequency content being produced by photons moving at the speed of light, with neutrons being somewhat slower, and with thermal effect being the slowest. Figure 2-6 shows the time domain of HEMP, and Figure 2-7 shows the frequency domain.

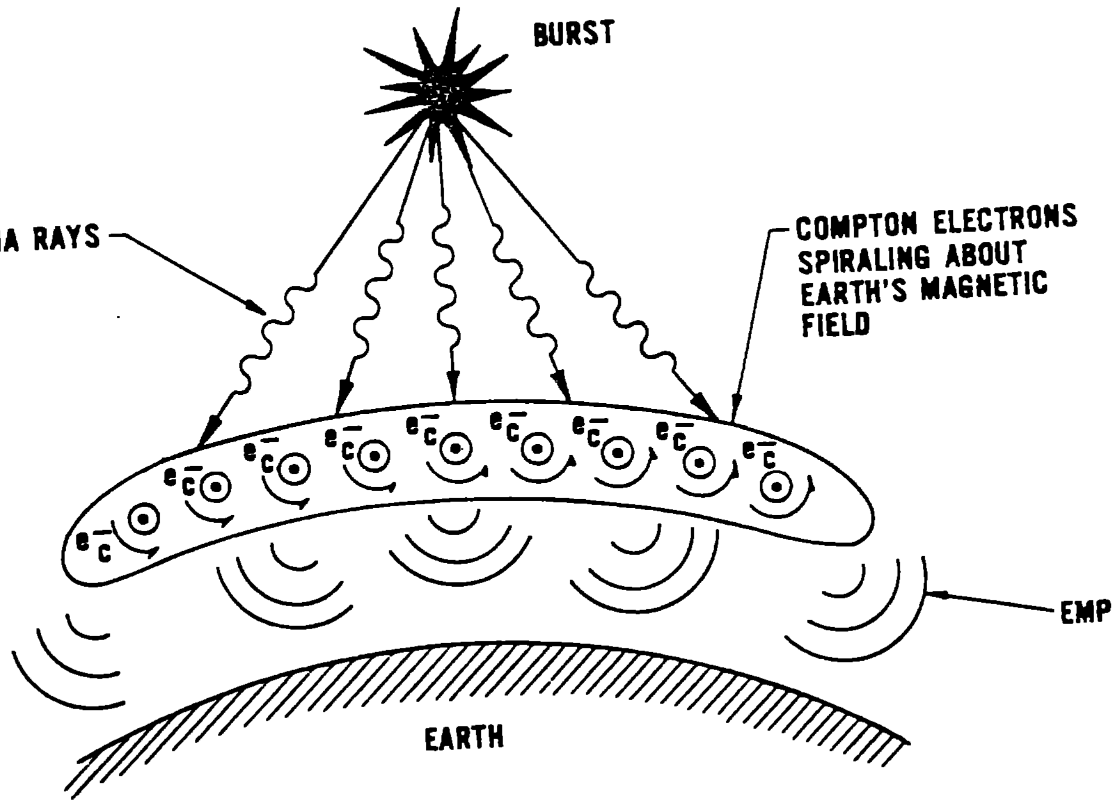


Figure 2-2. Exoatmospheric EMP source region.

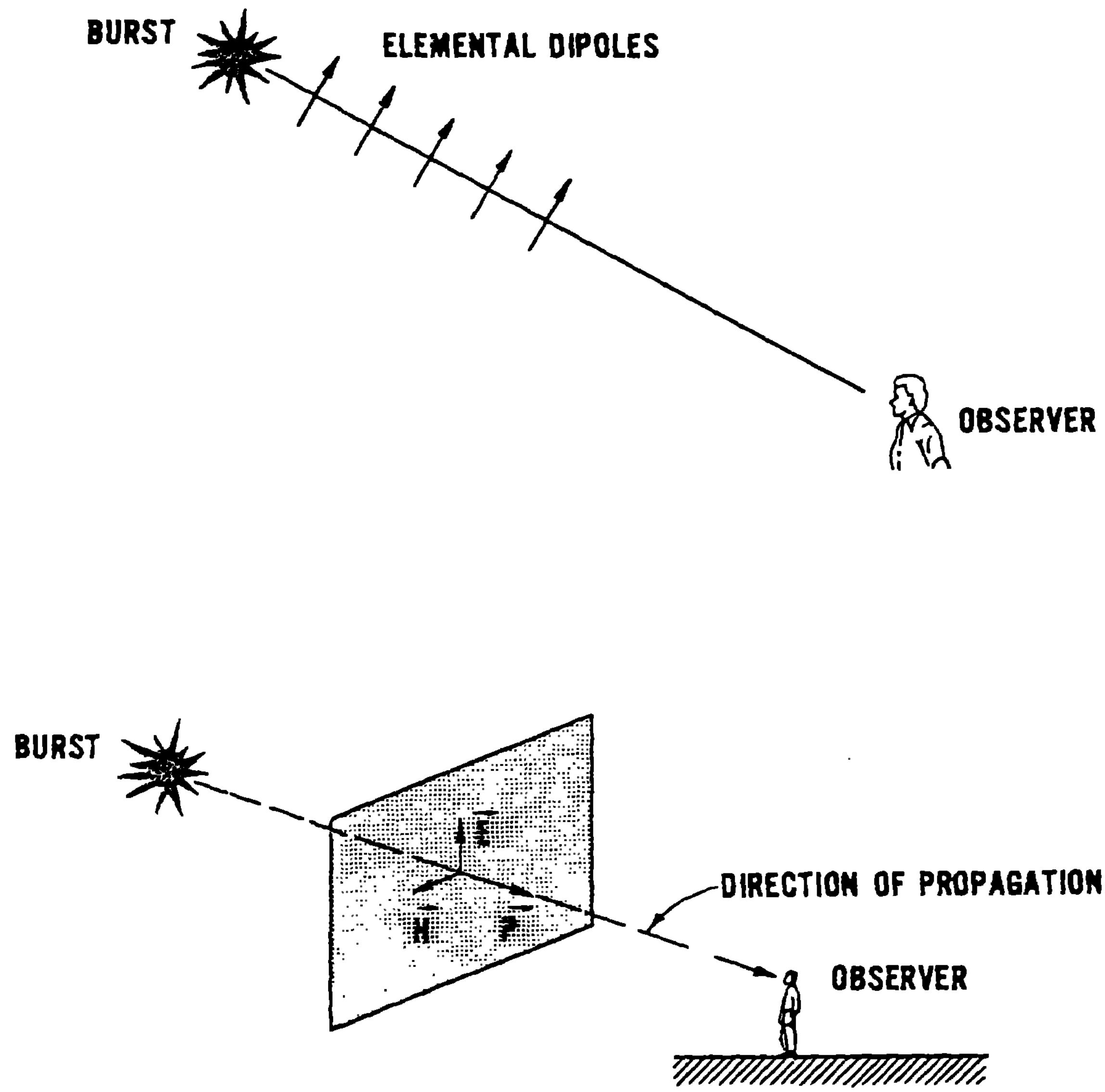


Figure 2-3. Phased array antenna model.

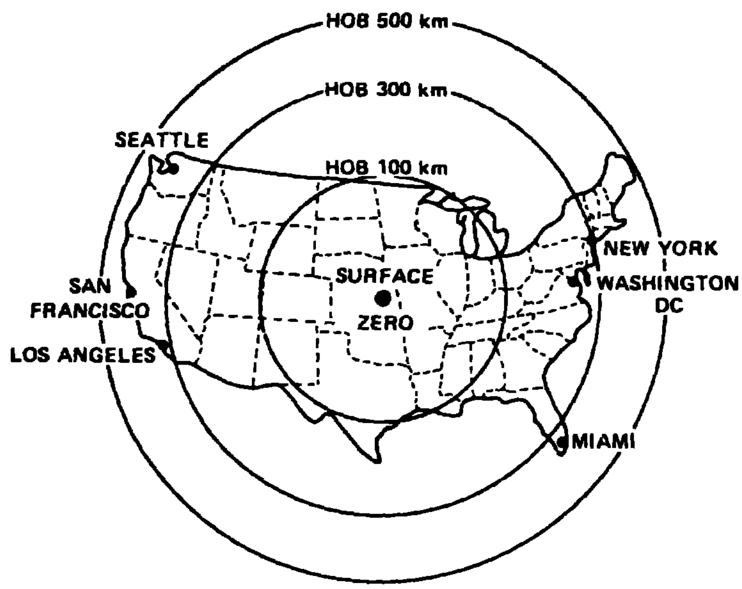


Figure 2-4. EMP ground coverage for high altitude bursts at 100, 300, and 500 km above the soil.

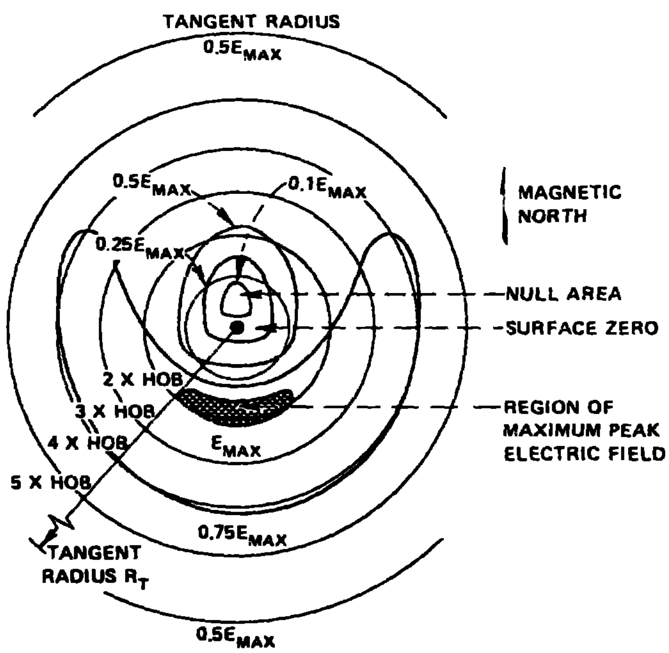


Figure 2-5. Variations in high altitude EMP peak electric field on ground surface.

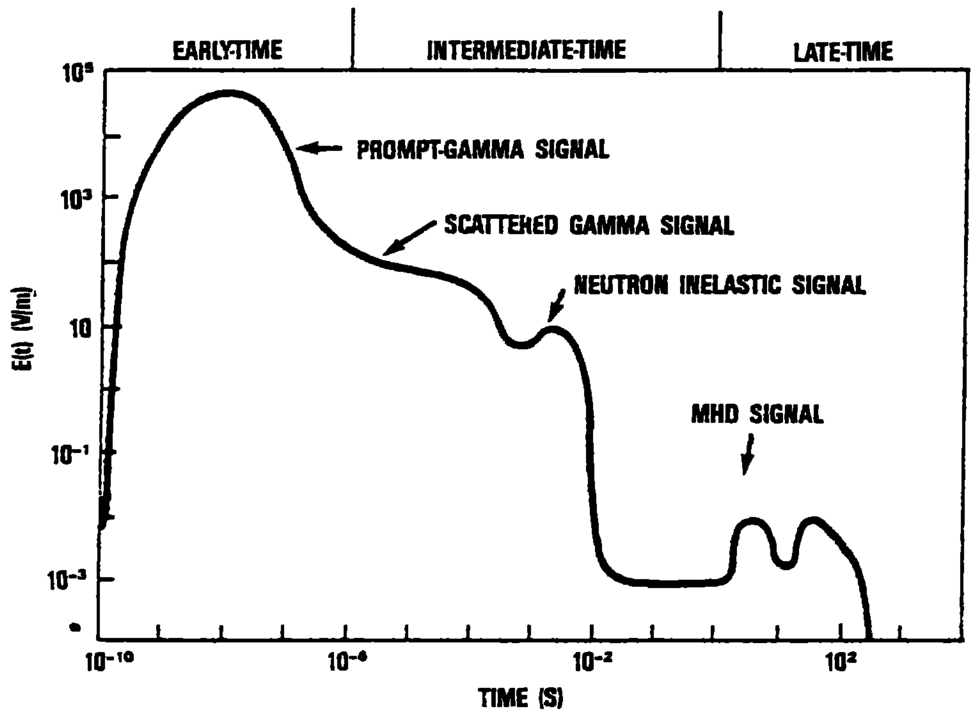


Figure 2-6. Qualitative time domain example of high altitude EMP.

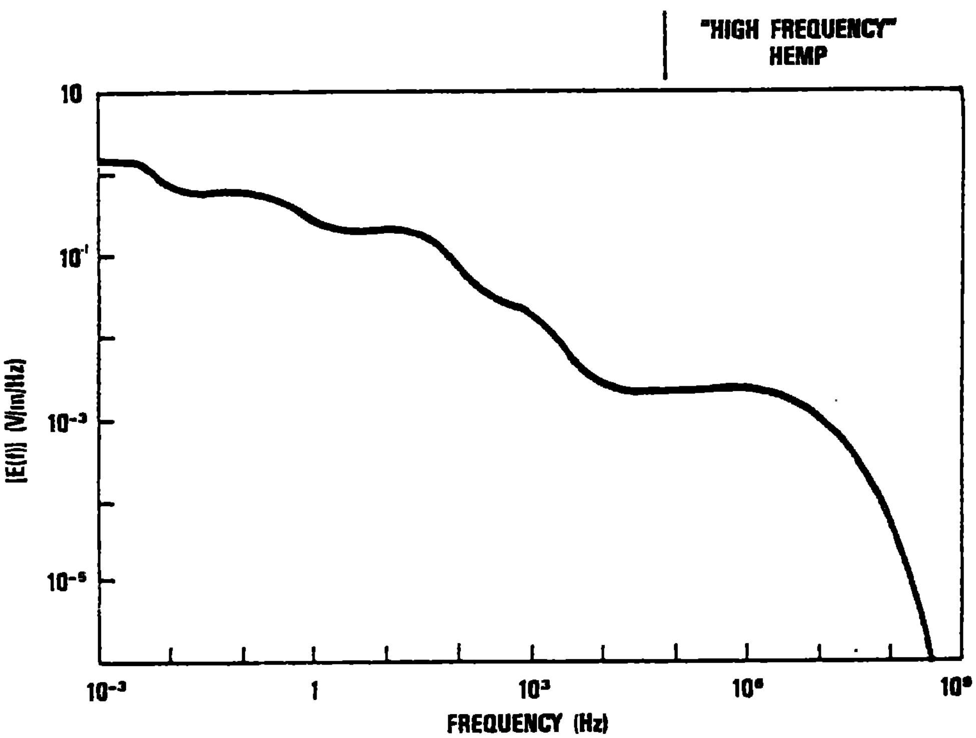


Figure 2-7. Qualitative frequency domain example of high altitude EMP.

MAGNETOHYDRODYNAMIC ELECTROMAGNETIC PULSE (MHD EMP)

The term used to describe the plasma physics effects of nuclear explosions is magnetohydrodynamic. This term encompasses all of the complicated interactions involved with expanding and rising fireball constituents. As the altitude of the explosion increases, the density of the plasma changes drastically, and at high altitudes the geomagnetic field plays a significant role.

From the Pacific high altitude tests it was determined that the hydrodynamic motions of the rapidly expanding bomb debris and hot ionized gases tend to exclude the earth's geomagnetic field. The various perturbations caused by this phenomenon produce time variations in the magnetic field, which in turn generate electric fields at the earth's surface. Numerous magnetometer measurements of the earth's currents produced by MHD EMP were made during the Pacific tests, some at Johnston Island directly under the explosions and others at various locations, including some at great distances from the bursts.

These data correspond with the theory that MHD EMP has two phases and is produced by two principle effects:

1. An ionospheric blast wave that deforms the geomagnetic field lines and thereby sets up the early phase of the MHD EMP, which reaches the earth's surface in about two to ten seconds and can be worldwide.
2. Atmospheric heave in which hot debris and air ions are moved across geomagnetic field lines causing large current loops to be formed in the ionosphere. These current loops can produce signals that can be observed over large areas of the earth's surface including regions at the magnetic conjugate points. This later phase of MHD EMP takes place from 10 seconds to 200 seconds.

These early and late time MHD EMP generation mechanisms are shown in Figures 2-8 and 2-9, respectively. An example of a qualitative time domain waveform is given in Figure 2-10.

Although the field strengths generated by MHD EMP are small, they occur over long time periods, and the spectral content is in the near dc to a few hertz frequency range. Because of this low frequency and the small amplitudes of these fields, only systems employing very long electrical conductors are of concern in studying coupling effects of MHD EMP. Low frequency fields, however, have very large penetration depths in both water and soil that will

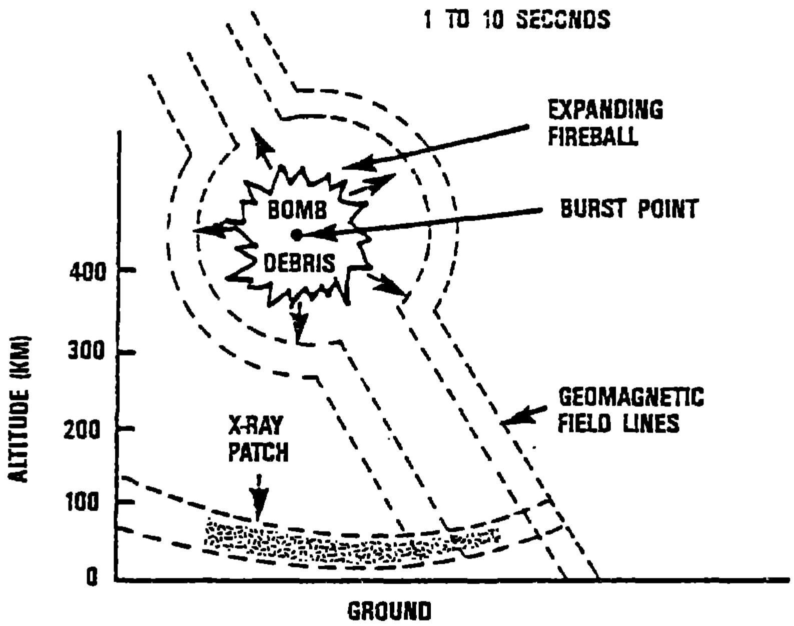


Figure 2-8. Early time MHD EMP generation mechanisms.

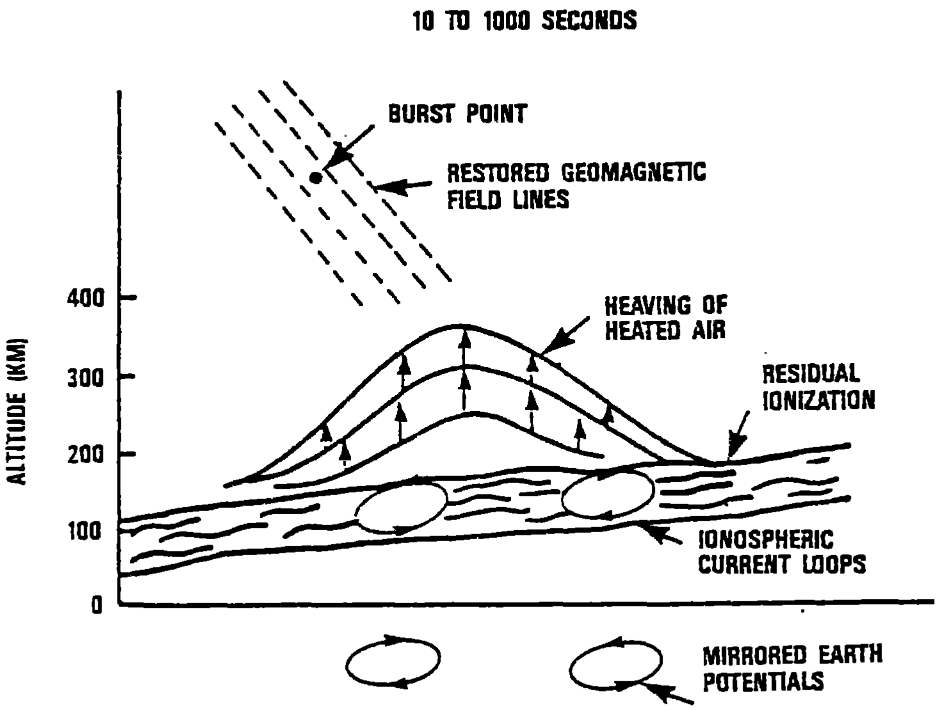


Figure 2-9. Late time MHD EMP generation mechanisms.

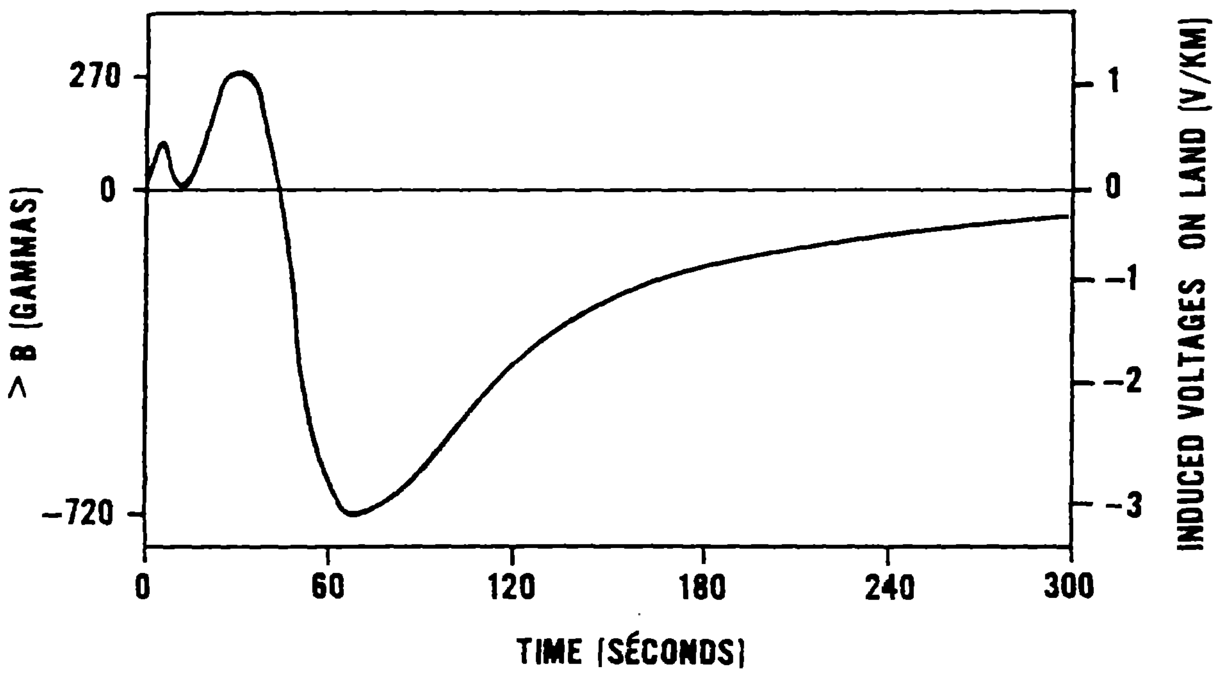


Figure 2-10. Qualitative time domain example of MHD EMP.

not serve as a shield as they do against high altitude EMP. If the induced voltages become high enough, typical cable systems can be disrupted or damaged (Figure 2-11).

SURFACE BURST EMP (SREMP)

Surface burst (less than 2 km above the earth) EMP is generated mainly by the asymmetry in the Compton current caused by the air-earth interface as shown in Figure 2-12. The deposition region ranges in radius from about 3 to 6 kilometers, depending on the size of the weapon. It contains a large radial electric field E_R and a very large azimuthal magnetic field $B\phi$ near the surface. Figure 2-13 shows a generalized time waveform of E_R and $B\phi$. Because of its high conductivity, the ground shorts the radial electric field near it, producing magnetic and transverse electric fields. These fields produce signals that radiate to great distances. As far as the radiated fields are concerned, the deposition region resembles a vertical dipole.

The electric field has a peak value of about 100 kv/m in the deposition region and a rise time of about 10 ns. In the radiating, region the peak value E_p of the electric field can be approximated by:

$$E_p = \frac{10^7}{R} \qquad R > 6 \text{ km}$$

Most of the energy is below 1 MHz in the frequency spectrum.

AIR BURST EMP

Air burst occurs between 2 and 20 kilometers above ground. The air density at these altitudes is relatively dense and quite uniform. Thus the asymmetries produced in the Compton current from both the geomagnetic field and the air density gradient are relatively weak.

The deposition region ranges from about 5 to 15 km, depending on the size of the weapon and the height of the burst. A large radial electric field is produced in the deposition region similar to that of the surface burst.

As far as the radiated field is concerned, the deposition region can be thought of as a vertical dipole. The radiated fields of the air burst are similar to those of the surface burst, with peak fields at least an order of magnitude lower than those of the surface burst.

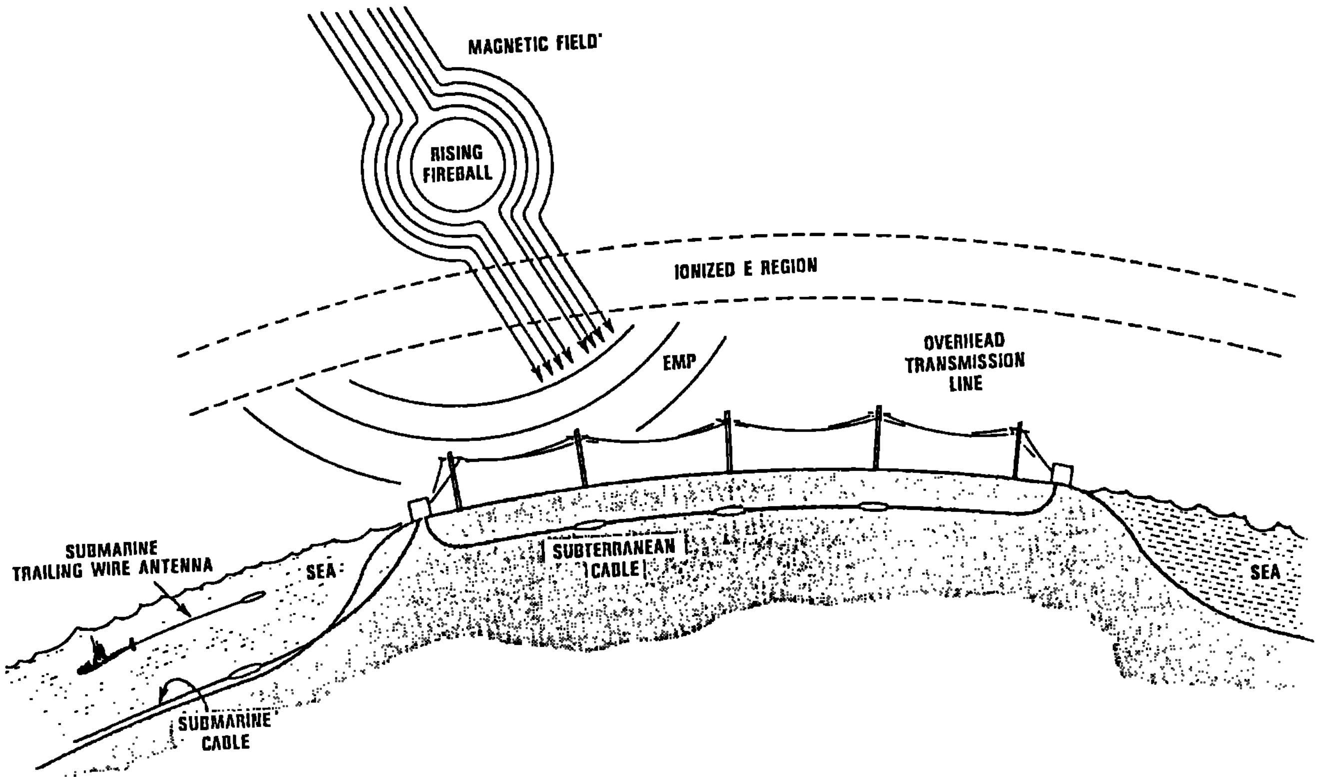


Figure 2-11. MHD EMP coupling method.

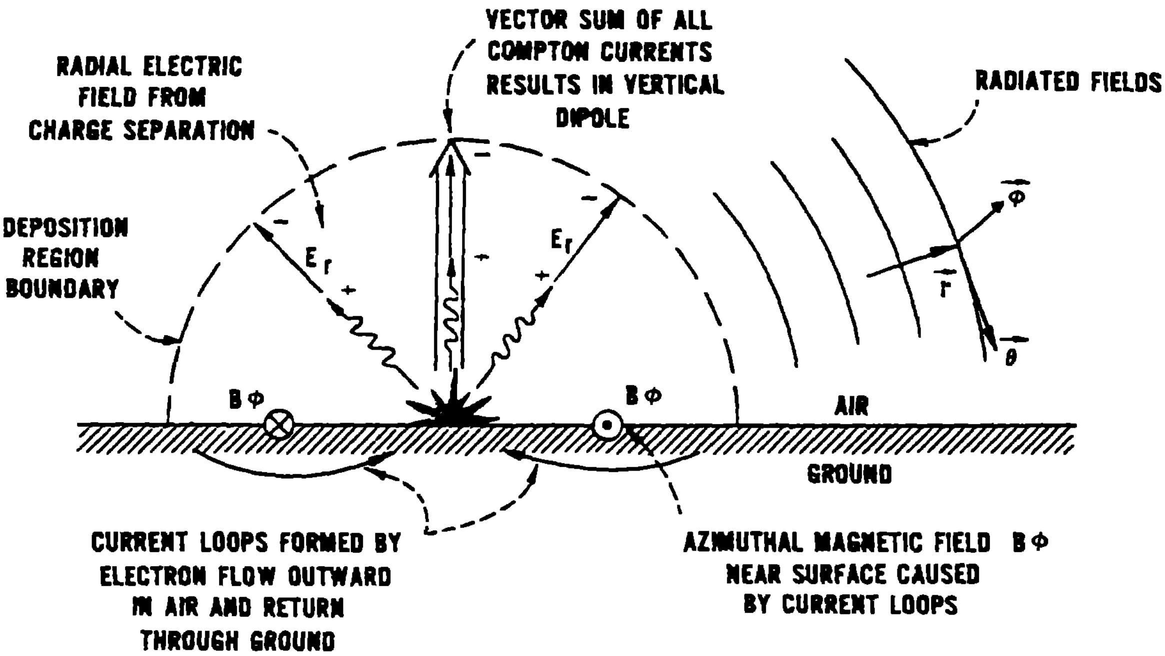


Figure 2-12. Surface burst EMP.

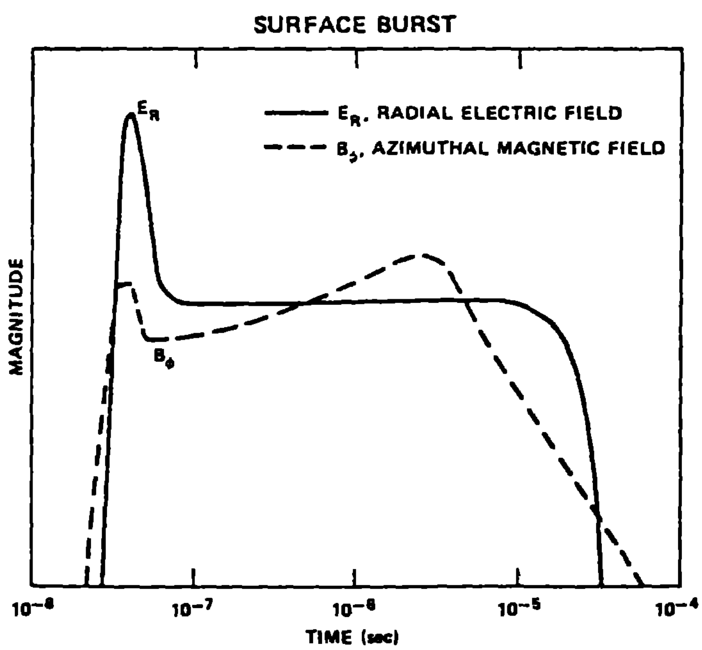


Figure 2-13. Generalized time waveforms of surface burst radial electric field E_R and azimuthal magnetic Field B .

OTHER EMP THREATS

High altitude EMP, MHD EMP, surface burst EMP, and air burst EMP are threats for ground based systems such as the civilian electric power network. The effect of nuclear lightning EMP produced by discharges similar to natural lightning appears to be significant on systems in the source region, but this threat is not taken into account in the determination of the vulnerability of the civilian power network.

Internal EMP and dispersed EMP are not of concern to the power network but represent a threat for systems such as missiles or satellites.

3. DESCRIPTION OF A MODERN ELECTRIC POWER SYSTEM

In a recent paper, Barnes, Vance, and Askins describe a modern electric power system as follows.[5] The function of today's modern electric power system is the conversion, transmission, and distribution of energy. The demands placed on the system are high reliability, flexibility, and low energy cost. To meet these demands, the utility industry has developed a vast integrated electrical system covering the continental United States. This system evolved from many smaller power systems that are interconnected to provide high reliability and to meet ever increasing demands for electrical energy.

A power system is composed of three major segments: generation, transmission, and distribution. Each segment is designed and constructed from components that have been designed and tested to ensure high reliability over a wide range of operating conditions and under various stress situations. The segments are coupled together at substations designed for switching and transforming power to differing voltage levels.

Besides these major segments, the operation and continuous monitoring of the power system requires an elaborate communication and control network. The equipment that makes up this network may vary in level of sophistication and age and may include state-of-the-art communication and computer equipment. Figure 3-1 is a block diagram of a typical power system configuration.

This section describes the basic elements and operation of commercial electric power systems. This will facilitate the identification and understanding of potential EMP impacts.

GENERATION, TRANSMISSION, AND DISTRIBUTION

Thermal (steam) and hydroelectric power generation are the main sources of electrical energy in the United States. The fuels for thermal generation are primarily coal, oil, natural gas, and nuclear power. Hydroelectric generation requires a head (height of water above turbine) of about 9 meters or more. The availability of sources of energy has a major influence on the location of the generation plants and usually results in the generation sites being dispersed throughout the area and in some areas that are remote from major load centers. Solar, wind, and geothermal power generation are now being developed; however, they are not major sources of electrical energy.

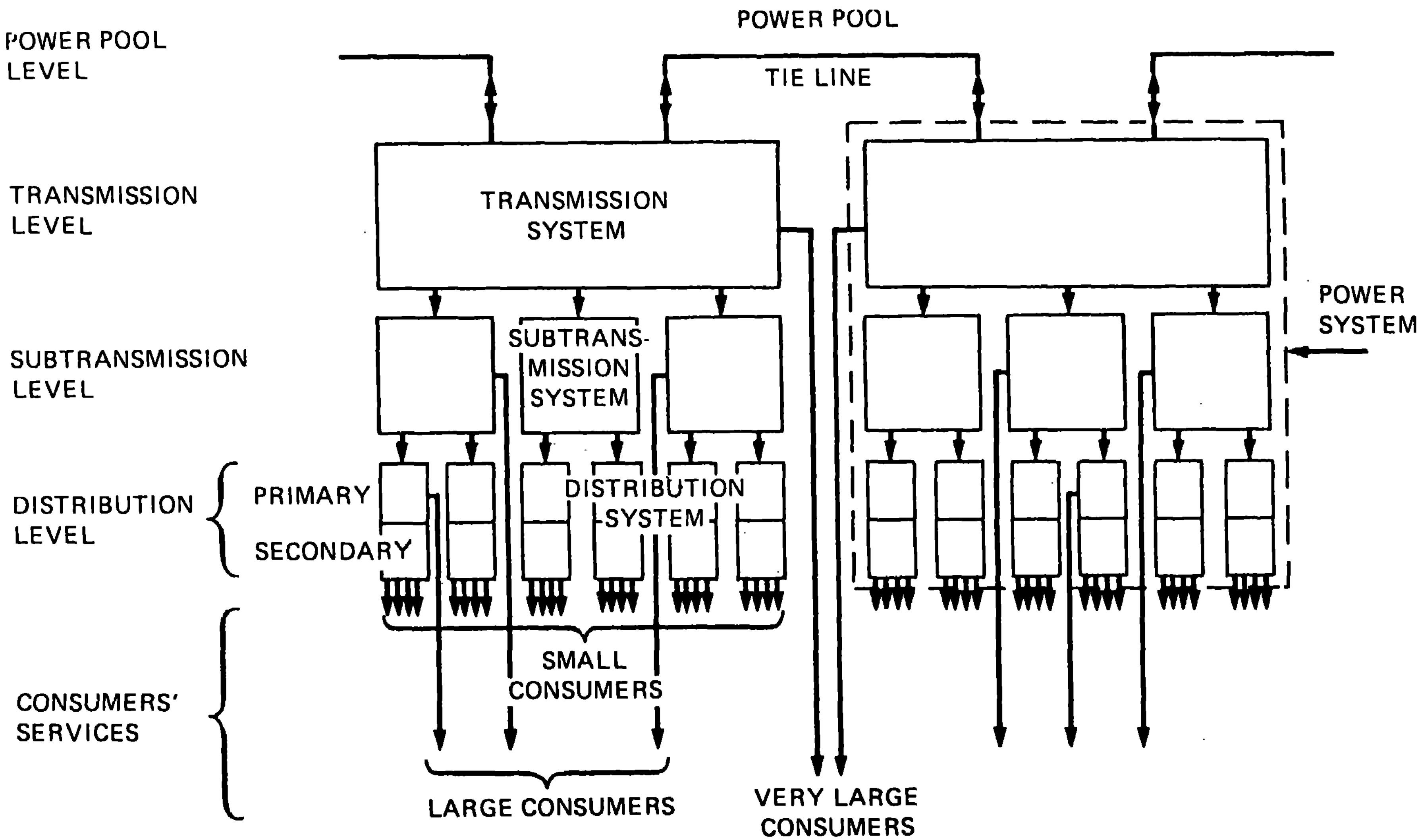


Figure 3-1. Block diagram showing the basic structure of the power system.

Generation plants usually are composed of several generation units. They may be hydro, nuclear, or fossil fuel units, or some combination. A generation unit consists of a turbine (steam, gas, or hydro) that is coupled to a three-phase synchronous generator. Generator output voltages fall in the range of 4 to 20 kV, and the power output can range from tens of kilowatts up to 2,000 megawatts.

The generation plant substation is the connection point for the generation and transmission segments. The output of the generators is connected to transformers through a three-phase conductor bus. Generator output voltages are stepped up to transmission voltage in the range of 138 to 750 kV for economical transmission of energy to load centers. Switches and circuit breakers are located in the substation to provide a means of connecting and disconnecting generators, transformers, and transmission lines, as required. Protection devices as well as monitoring, sensing, and control equipment are also located within the substation yard.

Transmission lines tie the power system together so that the generating capacity at various locations throughout the system is available to the load. The ac transmission voltage levels cover the range of 138 to 750 kV; the level depends on the amount of power to be transmitted and on the distance. Although both overhead and underground transmission systems exist, the underground systems are relatively short (less than 80 km) and have limited transmission capacity of less than 1,000 megawatts. The transmission capacity of an overhead line varies directly as the square of the voltage level. However, the actual line capacity may be somewhat less because of stability considerations. Overhead lines can be hundreds of kilometers long. Some typical overhead transmission line tower configurations are shown in Figure 3-2. The insulation characteristics of these lines are determined by the tower/conductor configuration, insulation string length, tower footing resistance and overhead ground wire locations.

The high voltage transmission lines are terminated in bulk power substations where the large blocks of power are received at high voltages and transformed to subtransmission voltage (34.5 to 138 kV) for delivery to various load centers. The subtransmission lines provide energy to a number of distribution substations central to loads in different geographical areas.

Distribution substations are fed from the transmission or subtransmission lines and vary in size and complexity. The principal components within the

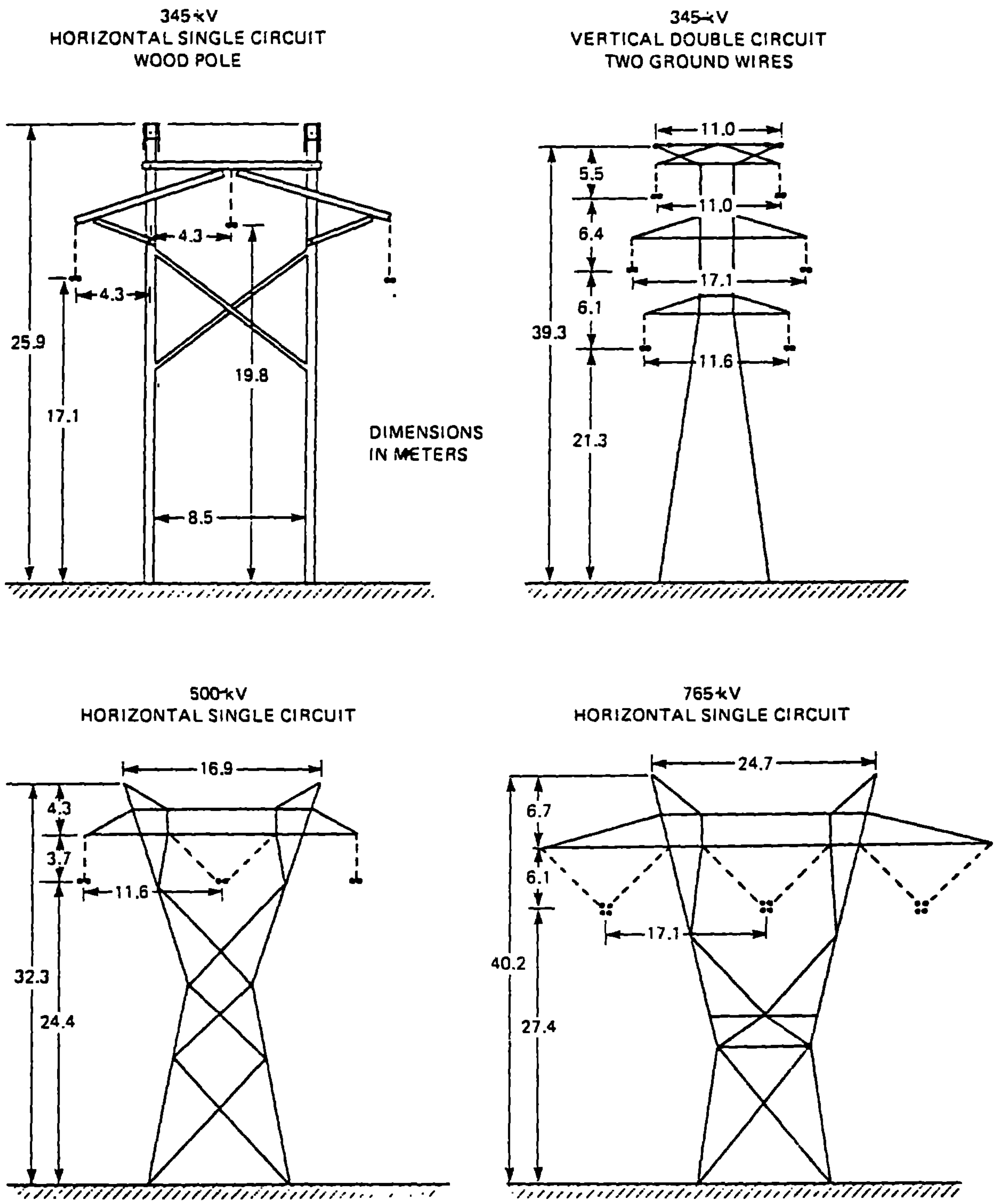


Figure 3-2. Typical overhead transmission line tower configurations.

station are transformers, high and low voltage switching equipment. Power received at distribution stations is transformed to primary feeder voltage (4 to 34.5 kV) for distribution.

The primary distribution lines may be arranged in several ways. Three of the most common are the radial, loop, and primary network systems. A large portion of the primary distribution system consists of radial feeders that leave the substation and branch off in all directions. The branches terminate at distribution transformers. In a loop system, the feeder leaves through one breaker and returns to the bus through another breaker. The primary network consists of a network of primary lines interconnected in the service area and fed by several breakers from two or more substations.

The secondary distribution lines consist of cables or wires from the distribution transformer to the customer load. The voltage level is normally 120/240V but can range up to approximately 600V. These secondary circuits may be overhead or underground or in radial, loop, or network layouts depending on many factors. Figure 3-3 illustrates a representative utility system and control hierarchy.

COMMUNICATIONS AND CONTROLS

Control of a power system requires maintaining voltages at various levels throughout the system as well as maintaining the frequency within very close limits of 60 Hz as the load varies. To accomplish these functions, complex control systems are necessary. For example, within the generation station, an extensive control system coordinates the steam turbine, generator, feed pumps, fans, and other auxiliaries to vary the rate of fuel with the variation in electric energy demand on the plant; the control system also keeps the shaft speed constant through wide load changes. Automated control of a typical plant involves the controlling, checking, and metering of more than 1,000 operations and parameters.

Throughout the power system at bulk and distribution substations, the monitoring of voltages and current flow is continuous. Protective relay systems detect trouble and initiate steps needed to open the proper circuit breakers to automatically isolate defective equipment from the system.

The continuous monitoring and control of the power system requires an elaborate communication network that is composed of several independent communication circuits: power line carrier communication systems,

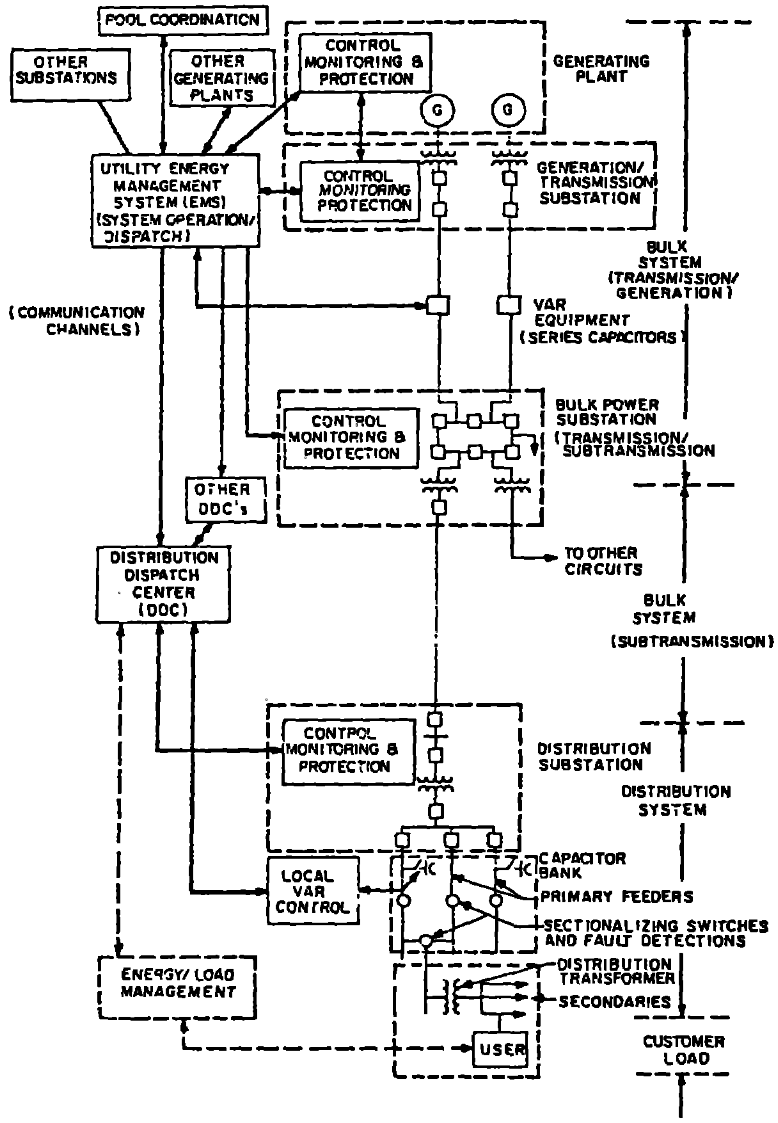


Figure 3-3. Representative utility system and control hierachy.

line-of-sight microwave communication networks, and hard-wired pair cable circuits. These systems are operated by the utility. In addition, existing telephone services are used. The power utility's communication circuits are used for pilot relaying, telemetring, control, voice channels, and computer data links. The telephone company's facilities are used mainly for voice and data communications.

OPERATIONS

Utility operations consist of two phases--operations planning and the real time operations of the power system. Operations planning is an off-line process that involves the commitment of generation and transmission facilities for use over the next one to three days. Real time operations involve the on-line management and control of generating units and transmission. The overall objective of utility operations is to ensure that the power system economically and reliably meets its load.

The purpose of operations planning is to develop a strategy for using the system's available resources to economically and reliably meet the anticipated load on the next day. Operations planning consists of two major functions--load forecasting and unit commitment. A load forecast is a prediction of the hourly loads and load ramp rates (minute-to-minute changes in load) for the next one to three days. The forecast is based on analysis of historical load data, evaluation of recent daily load, trends, and a weather forecast. Unit commitment is the process of selecting from the available generating equipment the specific units that will be used to meet the anticipated load. Frequently, the unit commitment function is performed by an optimization program that considers such factors as plant startup-shutdown cost, fuel cost, unit efficiency, and unit ramp rate. The output of the program is a mix of generating equipment that will allow the system to reliably follow long-term (hour-to-hour) and short-term (minute-to-minute) load variations while minimizing production cost.

On a daily basis, the load varies between a peak and minimum level. Figure 3-4 depicts a "typical" utility load profile over a two-day period. Based on the forecast hourly load profile and load ramp rates, the unit commitment program selects a mix of base load, intermediate, and peaking units suitable to meet the daily load.

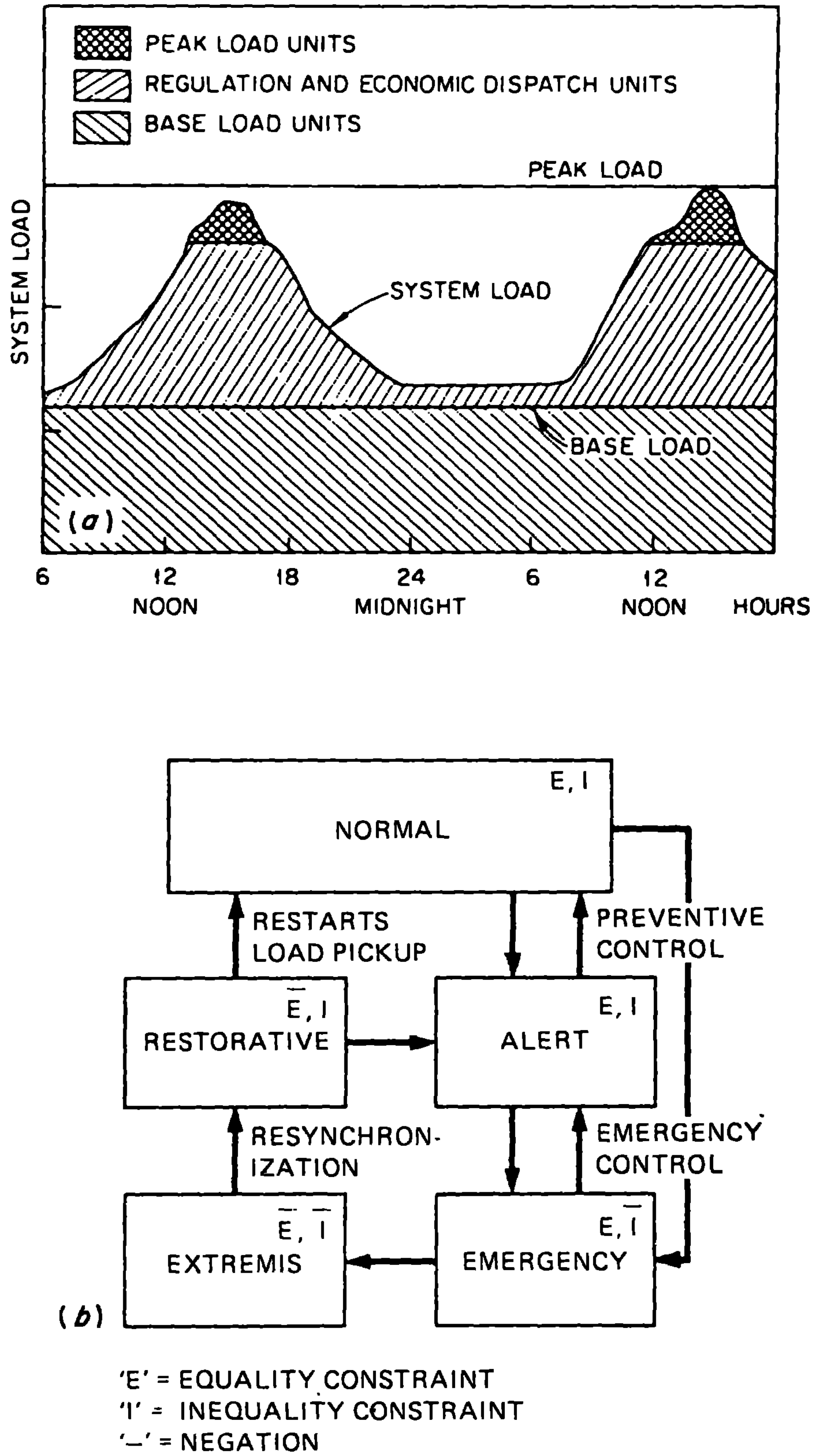


Figure 3-4. Electric power system load profile and operational states.

The daily real time operations problem for modern electric utilities is to continuously adjust generation to follow the load while minimizing cost. Balance between generation and load is achieved through the combined actions of speed governors on individual generating units (frequency regulation) and a closed loop automatic generation control (AGC) system, which performs load frequency control (regulation) and economic dispatch functions.

The key inputs of a utility's AGC are the deviations in frequency and tie-line power flow from their schedule values. To match area generation with area load requirements, a utility continuously monitors its area control error (ACE), which consists of the net tie-line power flow deviation plus a frequency bias constant times the frequency deviation. Non-zero values of ACE indicate that generation does not match load, and therefore corrective action is warranted. The general process of matching generation with load is referred to as load frequency control (LFC) or regulation. Generation/load mismatches should be corrected quickly to avoid excessive frequency deviations and possible adverse interactions with neighboring control areas. LFC provides for rapid generation/load matching using unit participation factors to proportion the area control error among the various generating units assigned to regulating duty.

In general, power system operations can be in one of five states: normal, alert, emergency, extremis, and restorative. Figure 3-4 diagrams the state transitions applicable to the various operational states. The five operational states can be related to electrical and mechanical constraints for electric power systems. The equality constraint E is related to the electrical power flow condition in which the real and reactive power of the loads and generation are balanced. $\bar{E}$ indicates that this condition is not satisfied. I is related to equipment constraints and limitations. $\bar{I}$ indicates that the maximum operating values for equipment have been exceeded.

In the normal state, generation is adequate to meet existing total load demand. This condition is indicated by E in Figure 3-4. No equipment is overloaded, and generation and transmission reserve margins are sufficient to provide an adequate level of security for the stress that may be imposed on the system. This normal state is indicated by I in Figure 3-4. The operators must continually adjust the level of operating reserves and reschedule generation to maintain necessary levels within initial geographical areas so that their system will be able to react and maintain its equilibrium when subjected to a disturbance. Utilities operate in the normal state over 99% of the time.

In the alert state, total load demand is met (E), and no equipment is overloaded (I). However, reserve margins are such that a disturbance could cause overloads. For example, transition to the alert state could occur if a generator is hot and the security level reduced. Preventive action can be taken to restore the system to normal.

The system is intact (E) in the emergency state, but overloads ($\bar{I}$) exist and/or equipment physical limitations are exceeded. Security is reduced to the point where emergency control measures such as reduction in bus voltages are required to restore the system to the alert or normal state.

In the extremis state the system is disintegrating ($\bar{E}$, $\bar{I}$). Generation and load equalities are not satisfied, and major proportions of the load are lost. Physical equipment overloads occur, and equipment limitations are exceeded ($\bar{I}$). Emergency control action is necessary to salvage as much of the system as possible and to minimize power disruptions and equipment stresses within the system.

The restorative state involves taking control actions to relieve overload ($\bar{I}$), to pick-up lost load ($\bar{E}$), and to reconnect the system. This process is slow and may take several days because it involves generator restarts, resynchronization, and gradual load pick-up.

In summary, the operation of a large interconnected power system involves simultaneously tracking the varying load, optimizing generation to minimize cost, and coordinating the action of many control systems. The complexity of the system requires the use of computers to aid in coordinating operations at different sites and processing large amounts of data for simulation, graphic display, decision making, and instantaneous closed-loop control. For example, graphic displays provide the operator with color coded system diagrams to indicate voltage levels, load and operating summaries, and special reports reflecting the system status at various stages of controlled events. Using information from the computer, the human operator (dispatcher) can interact with the system by switching generators on or off line, transferring power into and out of an area, and changing set points or control values to alter the real or reactive power flow.

POWER SYSTEM STABILITY

Power system stability is the property of a power system to return to normal or stable operation after experiencing some form of disturbance. Stability problems are classified by the type and nature of the disturbance.

In general, there are two classes of stability problems--transient and dynamic. Transient stability relates to the ability of the power system to remain in synchronism following a major disturbance such as loss of generating units, transmission system faults, or sudden and drastic load changes. Time constants associated with transient stability problems are of the order of a few seconds or less. Dynamic stability relates to the ability of the system to adjust to small variations and slow or gradual changes in operating conditions so as to remain in synchronism. Dynamic stability problems involve changes in time constants, ranging from tens of seconds to minutes.

PROTECTION

Power system protection can be separated into two distinct categories--overvoltage protection and overcurrent protection. Overvoltage protection is concerned with limiting the voltage stress on equipment resulting from transient overvoltages caused by lightning surges, switching surges, and temporary overvoltages. Overvoltage protection is obtained through the process of insulation coordination. The equipment and apparatus insulation strengths, the line design (i.e., tower/conductor configuration, insulator string length, tower footing resistance, and overhead ground-wire locations), and the substation design including the surge arrester locations and ratings are coordinated to ensure that equipment "withstand voltages" are not exceeded.

Equipment and apparatus protection levels are based on the standard lightning impulse test wave (1.2 x 50 μs) which rises to a peak value in 1.2 μs and decays to half peak value at 50 μs; the standard switching surge impulse test wave is 250 x 2500 μs. Hence, system insulation levels are directly related to these accepted standards, which do not address surges with very fast rates of rise.

Overcurrent protection is concerned with the isolation of a fault as quickly as possible to prevent or limit damage to equipment, to minimize the effects of the overcurrent on the system, and to maintain system stability.

This protection is accomplished through the integration of transducers, relays, and circuit breakers into protection systems. The power system is divided into zones, and various protection schemes are used depending on which part of the system is to be protected. The relays sense a fault from signals detected by the transducers and initiate steps to open the appropriate circuit breakers automatically so as to isolate the fault from the system.

Overcurrent, directional, and ratio relays are widely used in distribution and subtransmission protection systems. Differential relays are employed in protection schemes for transformers, generators, and buses. Pilot relaying, which is a form of differential relaying, is used to protect transmission lines. If an internal fault occurs on the transmission line, information is transmitted to the line terminals to initiate the simultaneous tripping of the breakers. Since the line terminals may be hundreds of miles apart, this relaying scheme requires the use of communication channels in the form of telephone circuits, power line carriers, or microwave channels.

Transient disturbances on a power system that initiate action of overcurrent protection schemes can cause a significant imbalance between generation and demand that can result in stability problems. If a mismatch of load and available generation exists, underfrequency relays in substations throughout the load area will sense a decrease in system frequency and shed load once the frequency drops below a predetermined value. Underfrequency relays are also used to initiate system separation or shutdown if an emergency requires action beyond load shedding.

4. EMP AND NUCLEAR POWER PLANTS

Studies have been made in the past to understand the interaction of EMP and nuclear power plants.[6,7] More recently, Ericson et al. conducted a study for the Nuclear Regulatory Commission on the Watts Bar Nuclear Power Plant in Tennessee.[8] This section discusses the objectives, limitations, summary, and conclusions of the Ericson et al. study, which was a joint effort of scientists from Sandia National Laboratories, Boeing Aerospace Company, Booz-Allen and Hamilton, Inc., and IRT Corporation.

OBJECTIVES

This effort was established as a scoping study to address the question of whether or not the effects of EMP from a high altitude nuclear detonation could adversely affect the safe shutdown capability of commercial power plants.

Therefore, the study had the following objectives:

1. To determine the vulnerability to EMP of systems required for safe shutdown of a specific nuclear plant.

2. To establish how shutdown systems that are vulnerable to EMP may best be hardened against it.

3. To characterize, to the extent possible, the effects of EMP on nuclear plants in general, using the results for systems in the example plant.

4.2 THE WATTS BAR NUCLEAR POWER PLANT

The Watts Bar Nuclear Power Plant in Tennessee was selected as the example plant for this study. This plant had been used in some earlier non-EMP studies, so a significant amount of data such as system fault trees was already available. The Watts Bar Nuclear Power Plant is a two-unit Westinghouse pressurized water reactor plant located on the Tennessee River. A plot plan showing key features is shown in Figure 4-1.

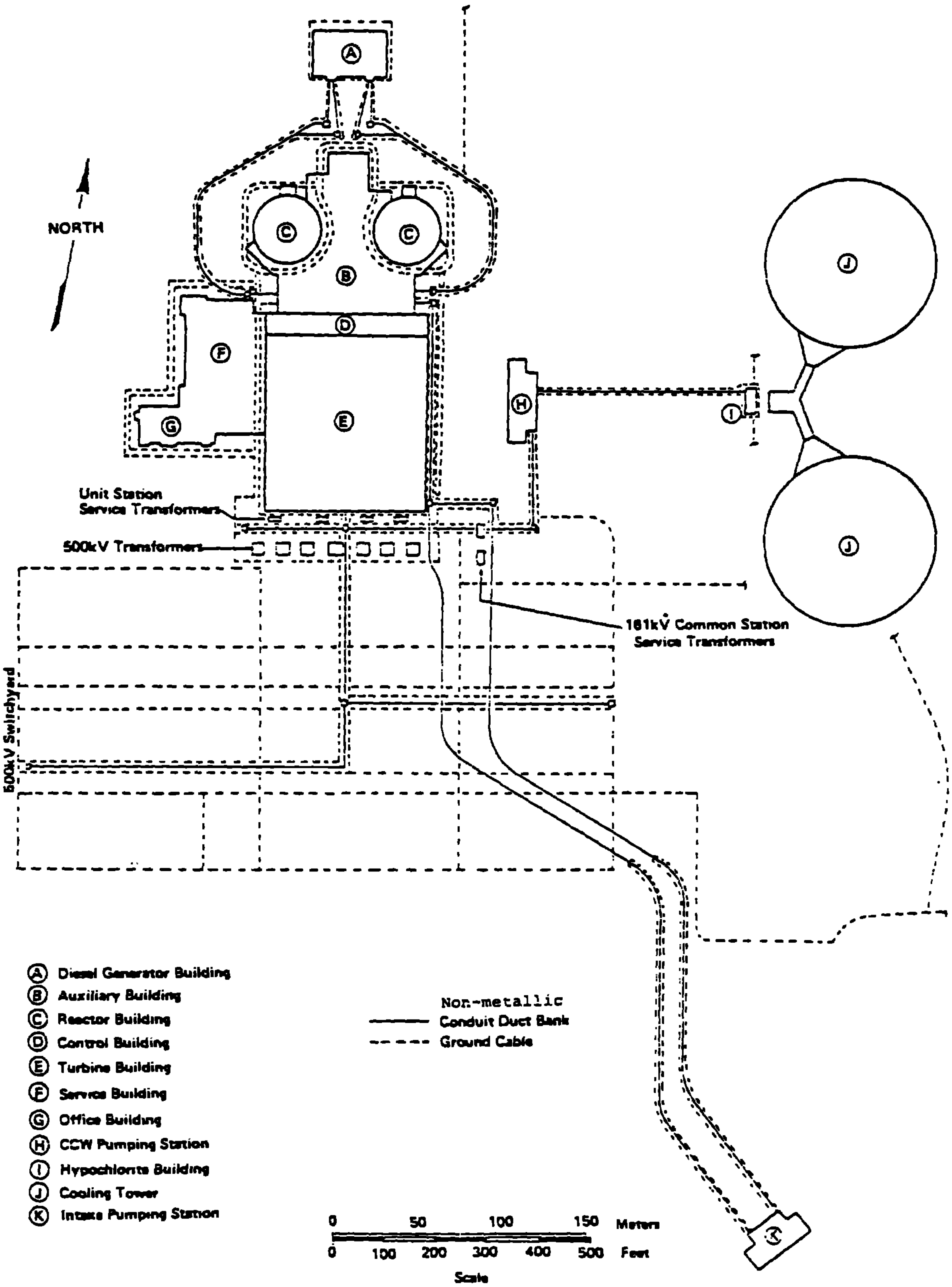


Figure 4-1. Plot plan of the Watts Bar Nuclear Power Plant.

Three essential functions must be accomplished to safely shut down a nuclear plant: the fission process must be terminated; the coolant inventory must be maintained; and decay heat must be removed. For the example plant, the systems required for safe shutdown include the following:

- Reactor protection system (the manual scram portion).
- An ac/dc emergency power source.
- Auxiliary feedwater system.
- Chemical and volume control system.
- Component cooling system.
- Residual heat removal system.
- Essential raw cooling water system.
- Heating, ventilating, and air conditioning systems (portions).
- Instrument air system (portions).

System analysis revealed that the ac/dc emergency power system is the "common denominator" of these systems. Therefore, subsequent EMP analysis focused on the ac/dc emergency power and the control and instrumentation subsystems of the remaining systems.

SUMMARY

Certain constraints and assumptions were adopted early in the work to keep the problem trackable, as follows:

- The study was limited to those systems required for safe shutdown of the nuclear plant. It focused on particular systems and on components that were representative of classes of equipment used in plant systems so that a detailed analysis could provide insight into potential vulnerabilities.

- The study was based on a "worst case" EMP threat situation that assumed that the incident EMP threat embodies a bounding peak field intensity and an orientation relative to the plant system such as to optimally excite every point of interaction.

- The magnetohydrodynamic EMP was not considered extensively in the study because the authors did not consider it a serious threat for safe shutdown.

- Permanent damage failure was the criterion used to assess system vulnerability. That is, signal upset effects were not considered in the study.

- No attempt was made to estimate damage thresholds for cables, power and distribution transformers, and rotating machinery. However, estimates of such thresholds based on available data were used in the vulnerability assessment.

- The damage threshold calculations were analytical only; no supporting component test program was conducted. However, the data base used included experimental data from previous programs, published threshold data, and data derived using empirical models and published device electrical parameters.

- Because semi-conductor devices generally have been shown to be more susceptible to EMP-induced failure than passive components, the failure threshold analysis focused on those devices and excluded the passive components.

- The failure threshold analysis was conducted with the damped sinusoid waveform at 1 MHz, chosen as a median value for the predicted dominant responses.

- Internal interfaces within individual modules or equipment cabinets were not included in the damage threshold analysis.

The principal source of EMP energy coupled to critical circuits in the plant is current induced by EMP on those cables that penetrate into the buildings. The current induced on a conduit system is shared by the various parallel cables and conductors in the conduit. Cables from the buried conduit systems are routed inside the plant for substantial distances in trays with other plant cabling that is not similarily excited. The cross coupling in these coincident runs diminishes the currents on cables penetrating from outside to critical equipment. As cabling is brought to a point of distribution, such as a bus board, incoming current tends to divide among the conductors attached to the bus. Therefore, as it propagates inward from a point of penetration, the EMP-induced energy tends to be dispersed throughout the interior cabling system, attenuated by ohmic loss and distributed at bus boards.

The penetration of diffused fields into the facility was examined analytically and experimentally, and it was concluded that the structures offered shielding of at least 30dB.

CONCLUSIONS

Ericson et al. concluded that the safe shutdown capability of the example plant would not be disabled by an EMP event. They also expressed the opinion that nuclear power plants in general would be able to shut down safely in the event of a high altitude EMP. This judgment was based on similarities in the design and construction of nuclear power plants and on conservatisms in the analyses. However, plants that include design features that enhance coupling with incident EMP would need further study.

5. DOE PROGRAM

The Division of Electric Energy Systems of the U.S. Department of Energy (DOE/EES) has formulated a program for the research and development of technologies and systems for the assessment, operation, and control of electrical power systems when subjected to nuclear electromagnetic pulses.[9] Those technologies and systems include simulation models, assessment methodologies, experimental methods and data, protection hardware, and special operation and control procedures for electrical power systems under the influence of EMP. The purpose of the program is to provide the theoretical foundation, data base, and analysis techniques necessary to understand the response of electrical energy systems to the threat and to minimize the influence of EMP.

Many of the technologies and systems developed under this program will be applicable to research on the general problem of protection and control of electrical power systems against major disturbances. Major disturbances include: electrical transients; acts of war, sabotage, and terrorism; large power flow interruptions; and malfunctioning subsystems. An important difference between an EMP event and other major disturbances is that the effects of EMP are distributed throughout the power system, whereas many other major disturbances are localized. EMP could simultaneously stress every element of an electrical power system, including generation, transmission, distribution, communications, controls, and loads.

High altitude EMP is the most significant EMP for electrical power systems because of its large area of coverage and value. However, the DOE/ESS program is also structured to assess the effects of surface burst EMP and magnetohydrodynamic EMP. Nuclear lightning is not taken into account.

PROGRAM RATIONAL

The necessity for the EMP program arises from two major national goals. These are to increase national security and to decrease the vulnerability of electrical energy systems to major disturbances.

National Security

The potential chaos that may be created by high altitude EMP has national security implications. During a period of national crisis, electrical power would be required to operate military installations, civil defense facilities, and critical industries. In addition, if EMP caused a disruption of the financial, manufacturing, retail, transportation, and communication industries, as well as basic utilities, serious economic and social consequences would result. Thus disruption of the nation's electrical power supply has grave implications.

Electrical Power System Vulnerability

The nation's electrical power system is highly vulnerable to major disturbances, and its vulnerability to large transients and subsystem malfunctions will increase as generation and transmission facilities are operated closer to their limits. Special operating and control strategies need to be developed as part of contingency planning for major disturbances. The technologies and systems resulting from the research program will contribute to the development of the special operating and control strategies needed for electrical power systems in the event of major disturbances.

PROGRAM OBJECTIVES

The DOE/ESS EMP program is designed to develop technologies and systems to enable electrical power systems to: 1) provide for essential loads for military installations, civil defense facilities, and critical industries; 2) reduce damage to the overall power system in the event of a disturbance, and 3) minimize power outage time to the public. The development of a systematic approach to accomplish these three goals is the objective of this program.

The specific objectives of the program are:

- To develop scientific and mathematical models for representing the influence of EMP on electrical power systems.

- To develop analytical methods for assessing the effects of EMP on electrical power systems.

- To develop a data base from simulation studies and experiments for characterizing power system response to EMP.

- To develop and evaluate measures designed to minimize the influence of EMP on electrical power systems.

- To provide information and recommendations for electrical power structural and operational requirements when subjected to EMP disturbances.

The technologies and systems that will be developed to achieve the program objectives include analytical and modeling techniques, assessment methodologies, protection hardware, and special operating and control strategies. Recommendations for protecting electrical power systems against EMP will result from this research program; however, the implementation of EMP protection and contingency strategies is not included as part of this program.

ORGANIZATION

The investigation of the potential effects of EMP on electrical power systems requires a broad range of expertise in power-system technologies and nuclear weapons effects. Therefore a number of government and industry organizations are involved, as shown in Figure 5-1. Their activities are presented in Figure 5-2.

SCENARIOS DEFINITION

To investigate the interaction of electromagnetic pulse with electrical power systems, the first step is to define scenarios. Four hypothetical nuclear attack scenarios have been defined by Legro and Tesche for the purpose of providing sample electromagnetic environments for an assessment of the effects of high altitude EMP, magnetohydrodynamic EMP, and surface burst EMP; they are not based on notions of what an actual attack might include nor on any strategic considerations.[10] These scenarios are of increasing complexity. Each new attack is identical to the previous one until such a time that an additional burst is added to complicate the environment.

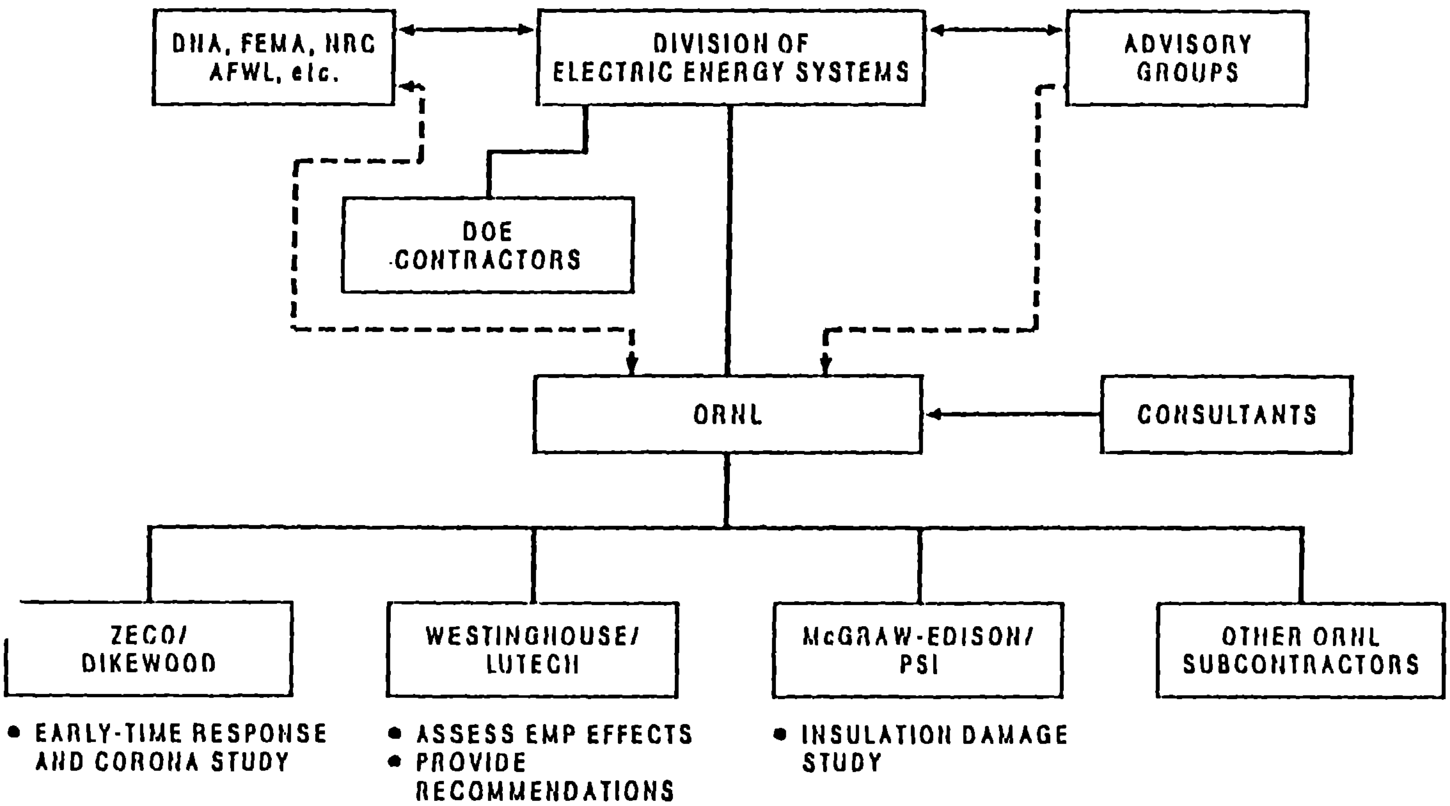


Figure 5-1. DOE/ESS EMP Program organizational structure.

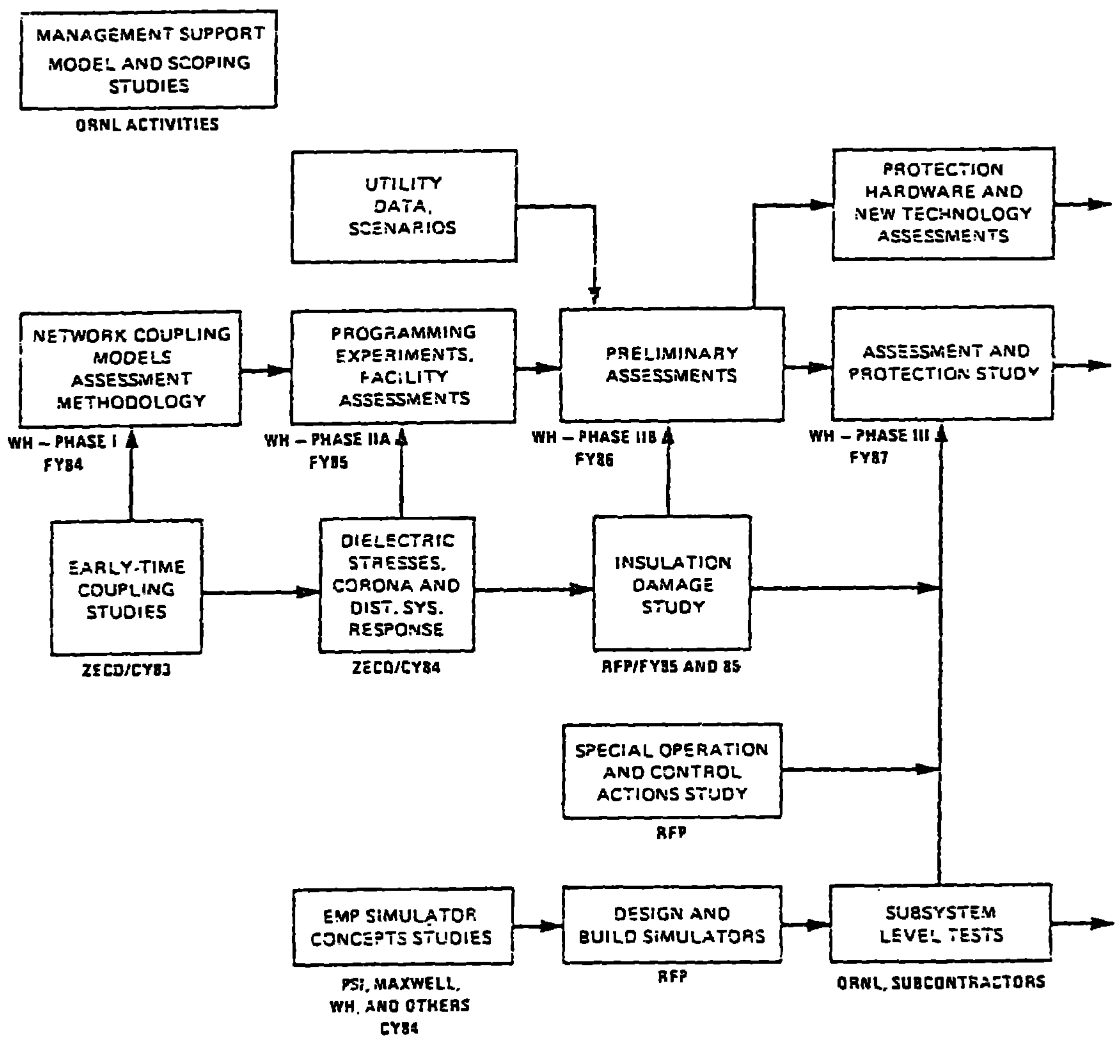


Figure 5-2. DOE/ESS EMP Program activities.

The four scenarios described by Legro and Tesche are:

1. Single high altitude burst--400 kilometers above Kansas.
2. Double high altitude burst--another high altitude burst is added above Utah one minute later.
3. Double high altitude burst and one surface burst--this scenario is identical to the second one for the first part, and a surface attack is added in Phoenix three minutes later.
4. Double high altitude and surface burst--a second surface burst is added fifteen minutes later in the Phoenix area.

The geographic locations of the high altitude and surface bursts are shown in Figures 5-3 and 5-4, respectively.

HIGH ALTITUDE EMP EFFECT ON ELECTRICAL POWER SYSTEMS

The energy of HEMP is coupled to sensitive equipment via structures and penetrations. Some of the most common penetrations involve overhead power distribution systems, telephone lines and cables, microwave towers and feeds, buried cables, water pipes, sewage pipes, gas pipes, doors, windows, ventilation systems, and many other openings in buildings.

The basic mechanisms by which the EMP energy is coupled to structures are:

- Electric induction, this is the principle mechanism for line conductors, the induced voltage dv produced by the electric field $\vec{E}$ on a linear conductor of length dl is: $dv = \vec{E}.\vec{dl}$
- Magnetic induction, which is the principle mechanism when the conductors' structure forms closed loops. The induced voltage is $v = \frac{A\partial B}{\partial t}$, where A is the area of the loop and B is the magnetic flux density.
- Aperture coupling, in which holes in structures provide a means for EMP fields to leak into the interior.

The phenomenology of coupling with conductors is now well understood and has been described in many papers.[11-14] For the power lines, the EMP pulse can reach several megavolts (open-circuit voltage) and several kiloamps (short circuit current). A typical waveform is shown in Figure 5-5.

Internal coupling is more complex and needs more research and development of tools, mainly in the theoretical area.[15]

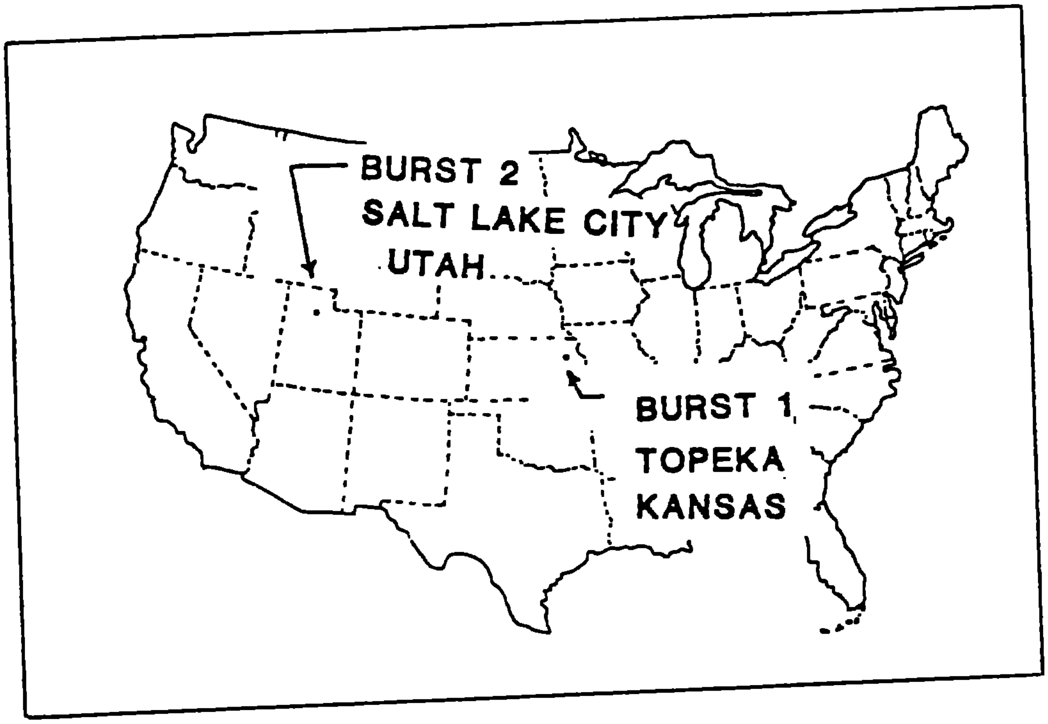


Figure 5-3. Geographic locations of high altitude bursts.

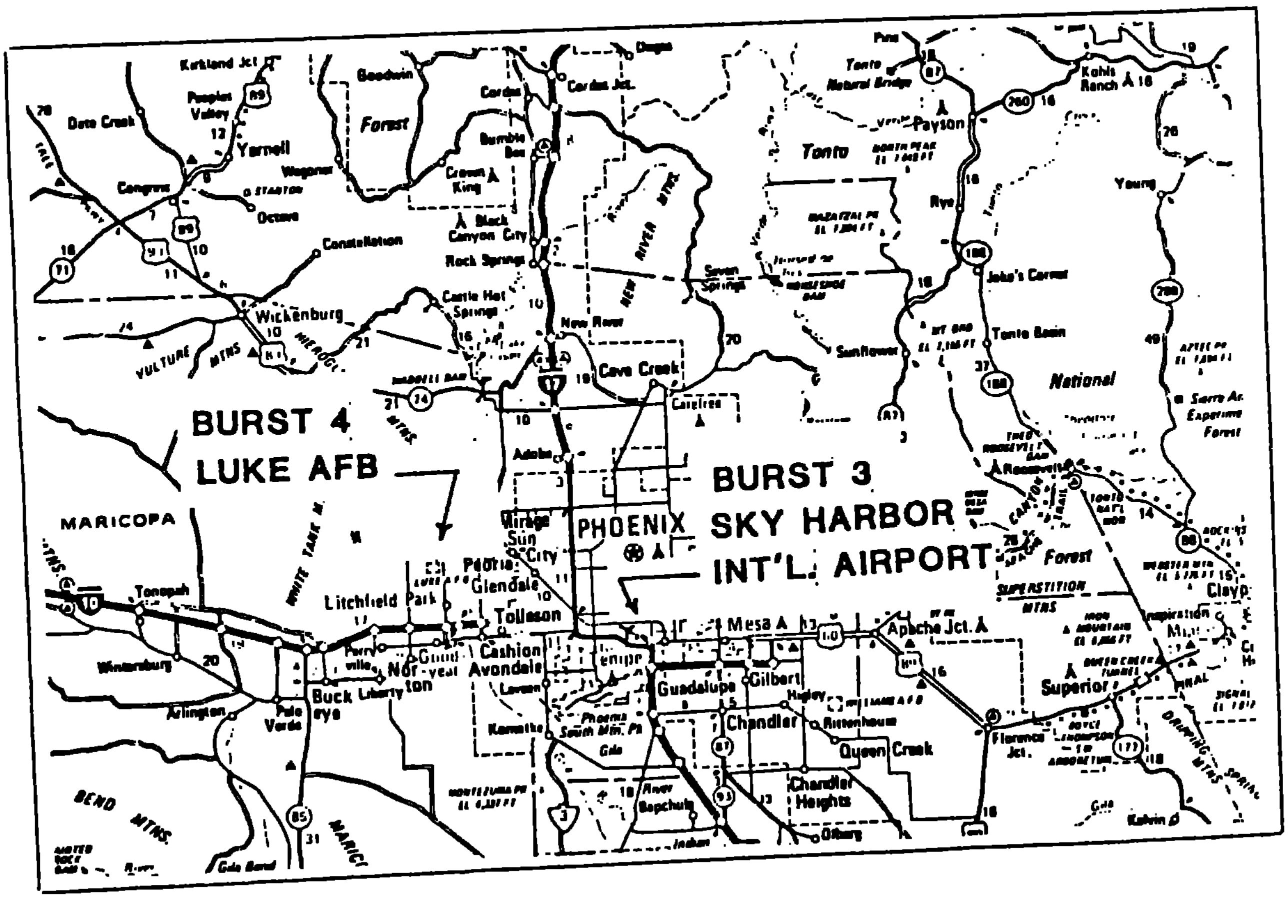


Figure 5-4. Geographic locations of surface bursts.

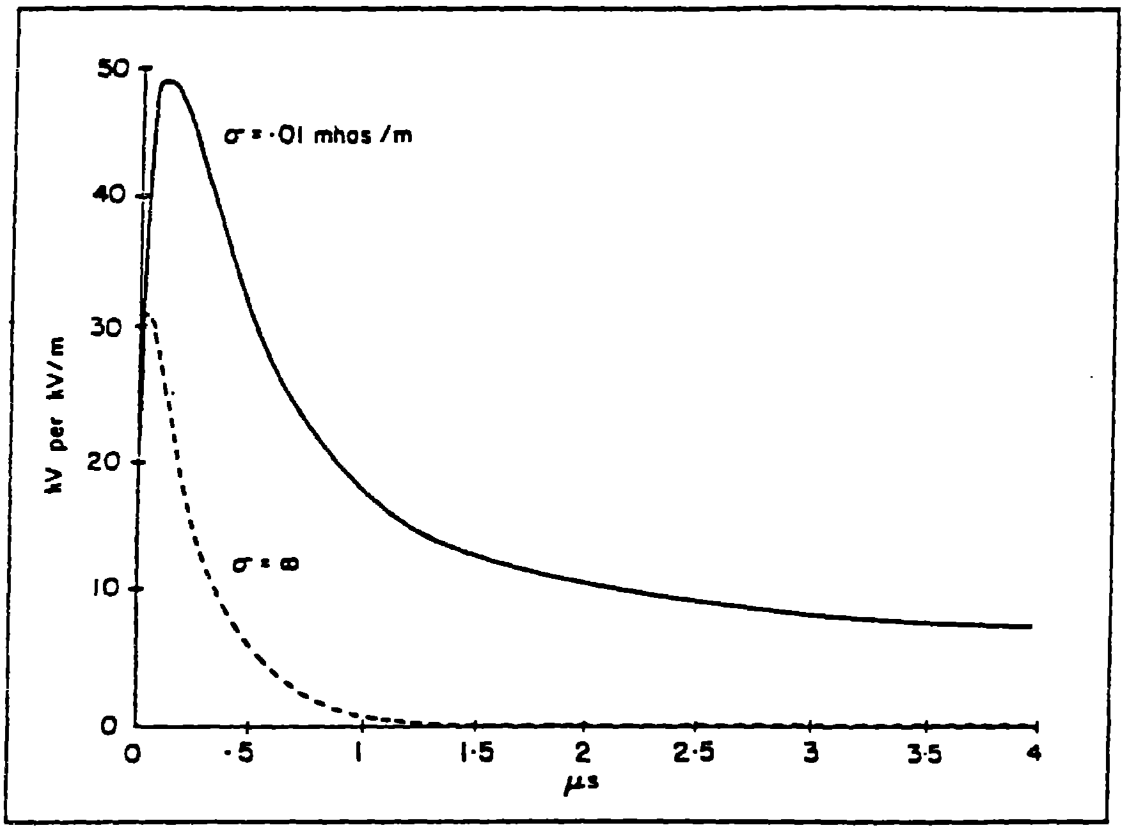


Figure 5-5. Typical waveform. (Normalized open circuit voltage induced on a long conductor 10 meters above ground.[12])

Elevation angle = 36°

HEMP plane wave oriented along the conductor

Vertical polarization

Solid line	soil conductivity	= 0.01 mho/m
Dashed line	soil conductivity	= 00

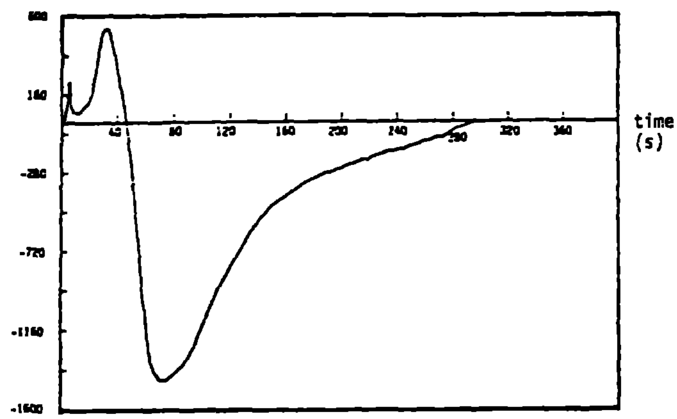
Now an effort is underway to understand and evaluate the influence of the corona on the response of long wires to HEMP.[16,17] Physically speaking, when the HEMP pulse "falls" on the wire, the electric current is induced in the wire and the radial component of the electric field is generated. If the radial component of the electric field on the surface exceeds the corona onset voltage gradient, Er, the corona discharge will take place and charged particles will be moving along the wire. This phenomenon affects the propagation of the pulse and, consequently, the induced current in the wire. In their paper, Engheta and al. clearly and mathematically explain the process of the effects using several corona models (Townsend's model, conductivity model, and Baum's model).[16] Each model has its own features, but all of them tend toward the same conclusion. The result is that the corona generally could reduce the peak value of the induced current by as much as 30% of the peak value calculated with usual methods. Some experimentations, now in progress, would validate these theories.

MAGNETOHYDRODYNAMIC EMP EFFECT ON ELECTRICAL POWER SYSTEMS

In order to understand and model the coupling of the MHD EMP electric field environment to the power system network, Legro et al. first examine the spectral content of the exitation.[13] Based upon the time domain plot constructed by Longmire for the magnetic flux density and corresponding electric field, a frequency domain plot for each was constructed. The results are shown in Figure 5-6. It is significant that even though the time domain MHD EMP has several rapidly rising spikes at elapsed times of less than 40 seconds, the corresponding spectrum is seen to contain only low frequency components of less than 1 Hz. In the case of magnetic flux (above 0.05 Hz), the spectral components are two orders of magnitude below the primary spectral components at lower frequencies.

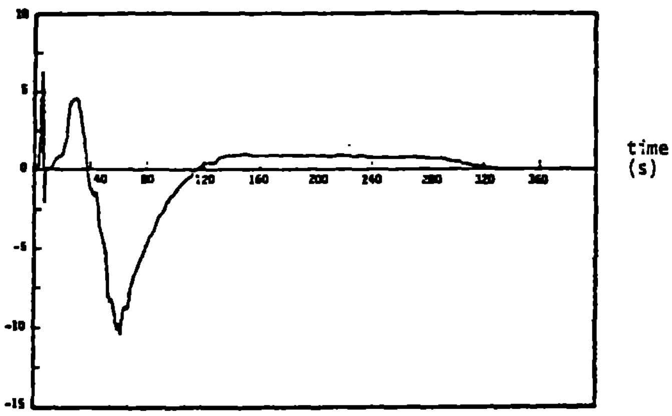
To assess the coupling mechanism of such excitation to the power system, one can consider an appropriate system response function. Such a function might be the respective current flowing in a conductor for a unit excitation in the frequency domain. If the transient behavior of this response function has a characteristic time which is less than the typical signal times, it is reasonable to construct a coupling model of the system using the dc concepts only. In the frequency domain, this implies that the network will have natural resonances at frequencies higher than those contained in the driving

Gammas



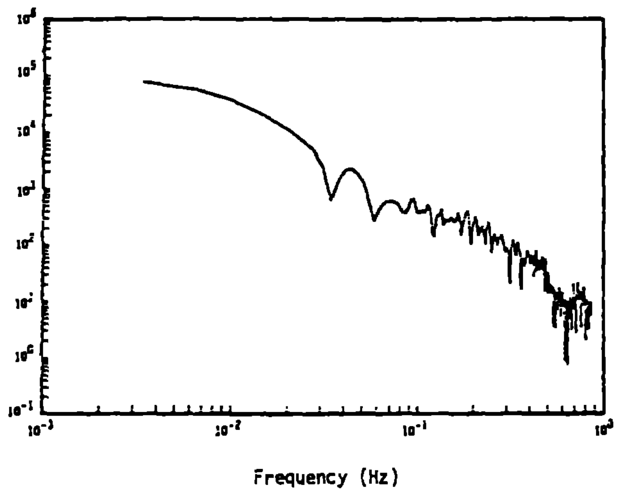
Time domain magnetic flux density.

$\frac{\text{Volts}}{\text{km}}$



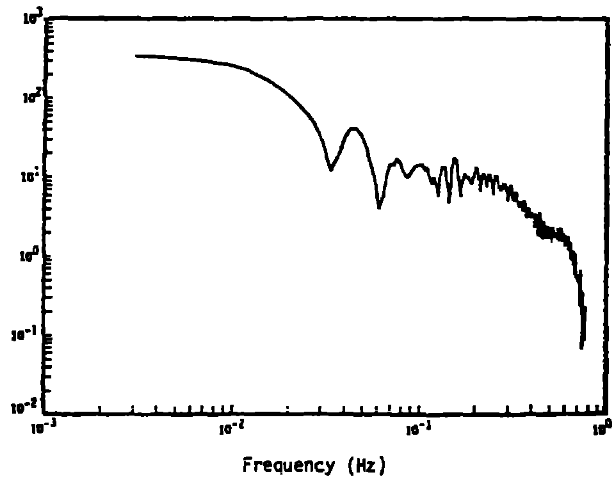
Time domain electric field.

$\frac{\text{Gammas}}{\text{Hz}}$



a) Magnetic flux density.

$\frac{\text{Volts}}{\text{km-Hz}}$



b) Electric field.

Figure 5-6. Time domain and frequency domain shape.

waveform and that a constant is all that is needed to represent the system coupling response. A reasonable break point frequency for power system networks is on the order of 0.1 Hz. Thus, the MHD EMP spectral distribution suggests that a reasonable coupling model may be constructed where the electric field of the excitation and the network topology for coupling is a multiple source, dc resistive network.

In their paper, Legro et al.[13] suggest representing MHD EMP by a product of three independent terms, as follows:

$$E(x,y,z,t) = \Sigma(x,y) \quad \bar{e}(x,y) \quad \mathcal{f}(t),$$

where

$\Sigma(x,y)$ represents the spatially dependent, time invariant magnitude of the field,

$\bar{e}(x,y)$ is a unit vector describing the spatially dependent, time invariant direction of the field, and

$\mathcal{f}(t)$ describes the time dependent, spatially independent behavior of the field.

This model is in good accordance with the MRC starfish simulation surface electric field; $\Sigma(x,y)$ and $\bar{e}(x,y)$ are described in Figures 5-7 and 5-8.

The concept of MHD EMP power system excitation and the computation of the response current is illustrated in the following example. Consider a hypothetical 161 kV single circuit (three phase) line connecting substations A and B. The spatial orientation of the line and the MHD EMP electrical field environment is shown in Figures 5-9 and 5-10. The location of the burst is at the origin coordinates (0,0). For this example, the line parameters are: L = 170 kilometers, Rdc = 10.2 ohms (0.06 ohm/kilometer). At each substation the line is terminated as shown in Figure 5-11. The YΔ winding configuration serves to isolate the 161 kV line from the remaining grid for a dc analysis. Each winding resistance R_Y is equal to 0.18 ohm per phase. An additional termination ground resistance equal to 1 ohm for a YΔ winding neutral to a remote ground point exists at each substation.

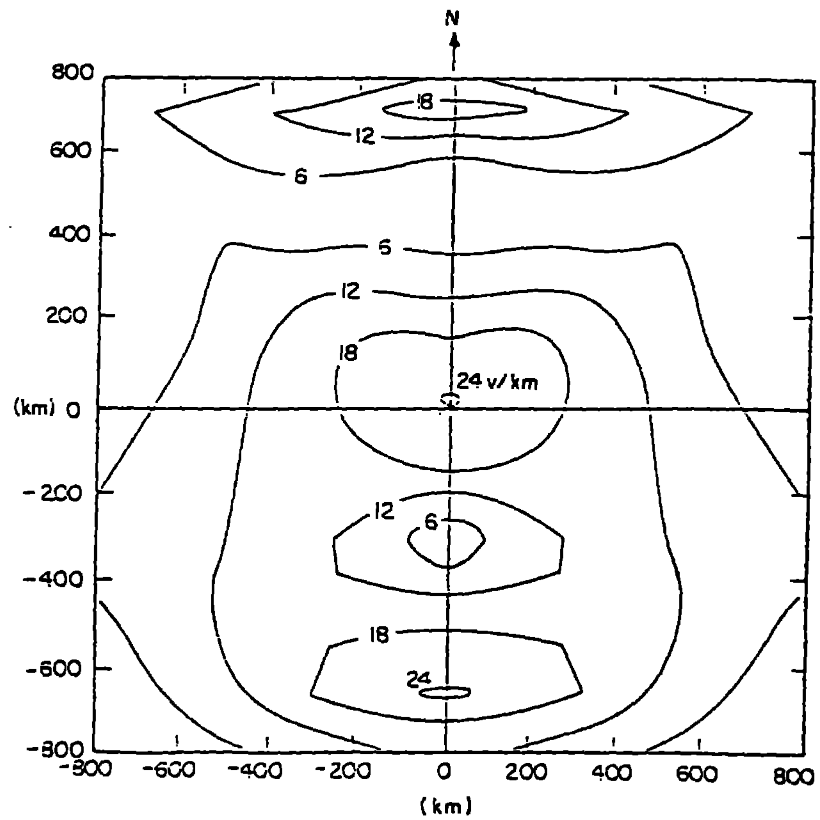


Figure 5-7. Magnitude function $\Sigma(x,y)$.

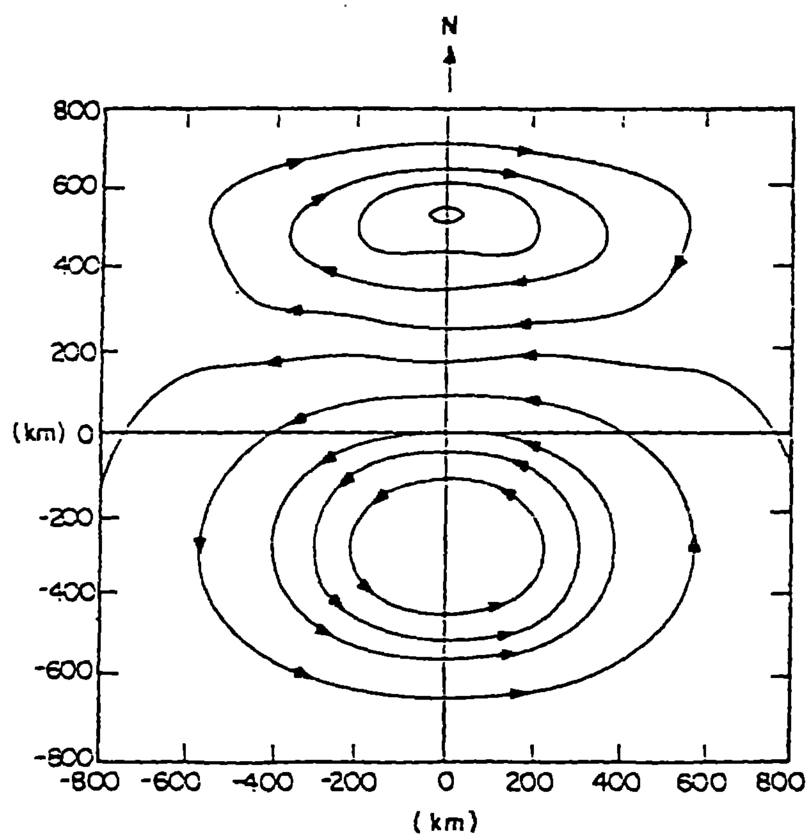


Figure 5-8. Unit vector function $\overline{e}(x,y)$.

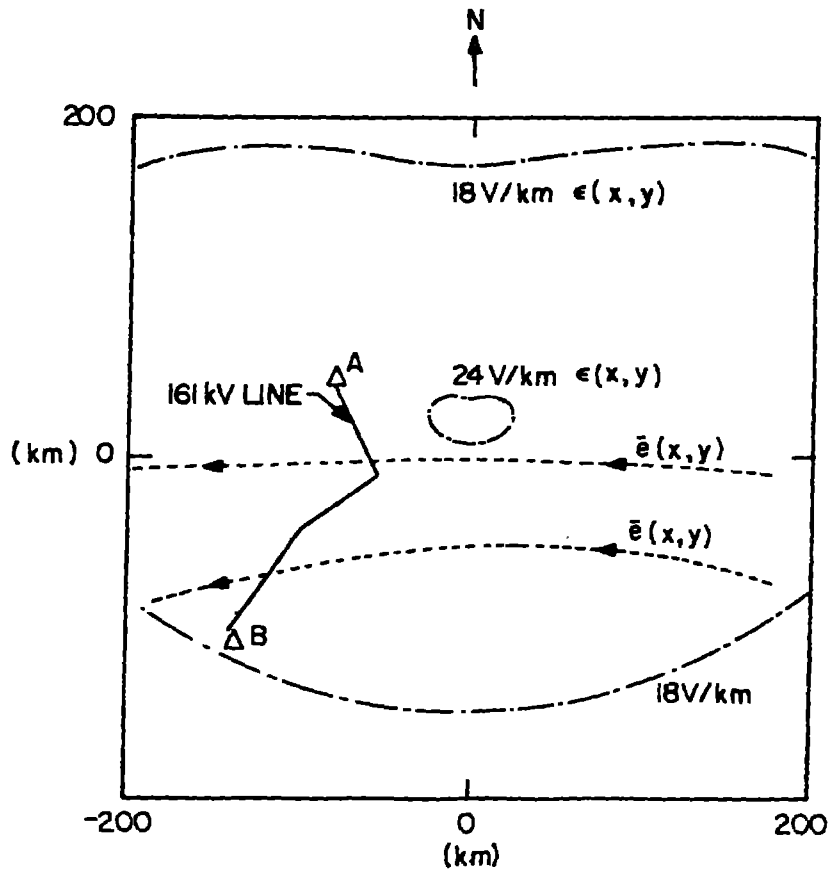


Figure 5-9. Spatial orientation of the line.

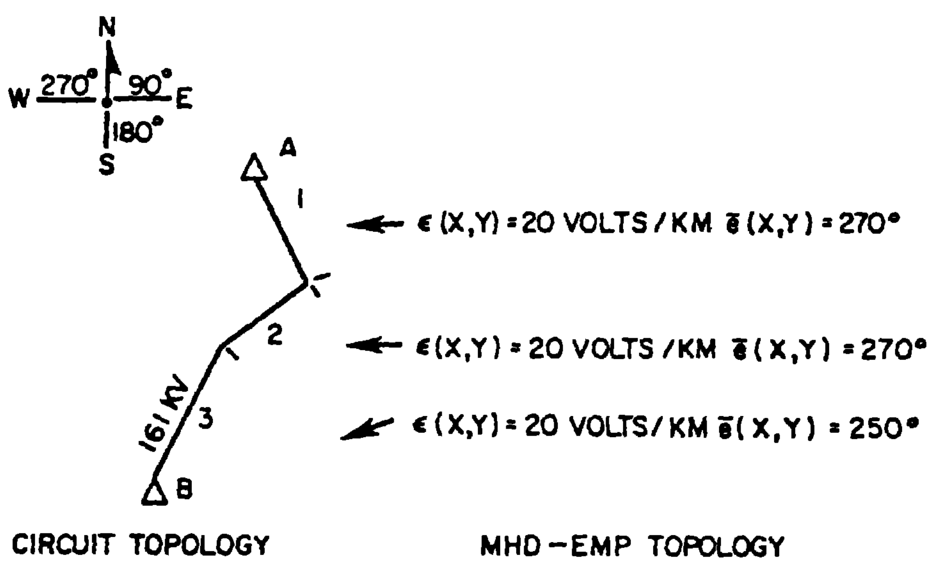


Figure 5-10. Segmentation of the line.

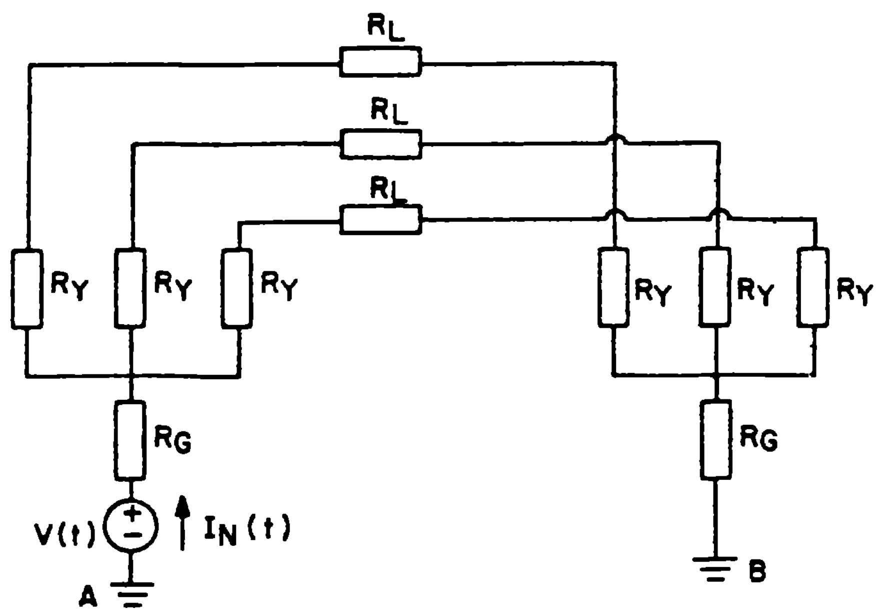


Figure 5-11. Direct current (dc) model of the three-phase line.

The dc circuit model is shown in Figure 5-11. To facilitate calculation of MHD EMP field coupling to the 161 kV line, the line has been partitioned into several segments (Figure 5-10). By translation of the equivalent north-south and east-west components of the line and the exciting field ($\simeq 20$ V/km everywhere), it is easy to calculate the equivalent generator (Figure 5-12). The neutral current is computed using Ohm's Law. In this example, IN is equal to 268.5 amperes, and for each phase the current is one-third of this value.

SURFACE BURST EMP EFFECT ON ELECTRICAL POWER SYSTEMS

The environment for the surface burst was briefly discussed in Section 2.

Because of the principle of balanced survivability, it is not necessary to evaluate SREMP effects directly on the system within the source region.[14] The important issues are:

- The threat associated with electrical surges formed within the source region and propagating out of that region via overhead and underground lines and cables.

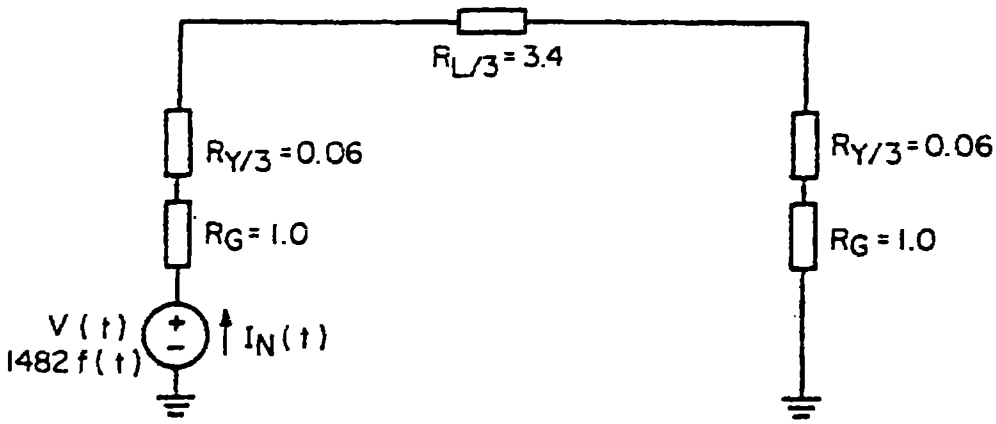
- The threat associated with the SREMP radiated field in the form of surge transients induced on power system elements located outside the source region.

- System operational capability and response due to the physical destruction of power system elements within the spatial radius of direct damage.

Coupling Within the Source Region

The calculation of coupling with lines in this region continues to be a topic of extensive discussion among EMP specialists.

An example of results is given in Figure 5-13 by Longmire for an overhead line and an underground cable, each 1,000 meters long in a nuclear surface burst region.



$$I_N(t) = \frac{1482\, f(t)}{2(R_G + R_{Y/3}) + R_{L/3}} = \frac{1482\, f(t)}{5.52}$$

$$I_N(t) \simeq 268.5\ f(t)\ \text{DC AMPERES}$$

Figure 5-12. Calculation of the MHD EMP neutral current.

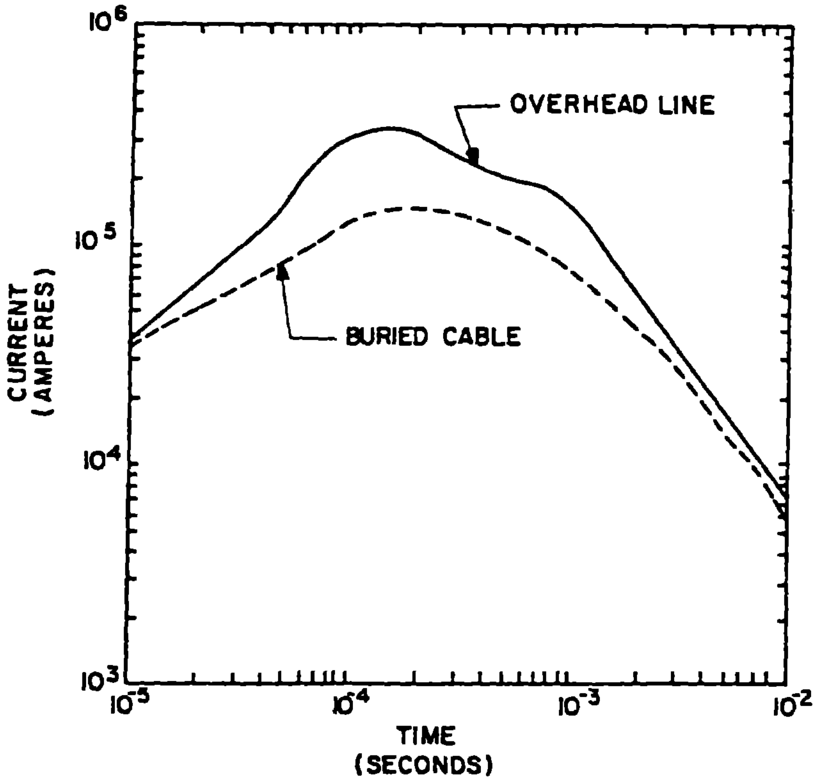


Figure 5-13. Longmire example of an overhead line and an underground cable, each 1,000 meters long.

Graham has calculated the current surge (Figure 5-14) across an 0.1-ohm impedance at the end of a 2,500-meter overhead line at 10 meters above the surface. In this presentation, no flashover is assumed to occur. The result is:

- Current surge peak magnitude ($E_\theta = 0$) of approximately 180 kiloamperes.
- Time to crest greater than 250 microseconds.
- Significant low frequency energy content.

E_θ effects are seen to decrease the peak magnitude of the surface due to field cancellation.

Barnes has suggested that the surge might generally be represented as a double exponential waveform, for some distance greater than 2,500 meters, as:

$$I = I_0 \left(e^{-\tau t} - e^{-\lambda t}\right)$$

where $I_0 = 180.3$ kiloamps,

$\tau = 3.8\ 10^{-2}$ second^{-1}, and

$\lambda = 2.10^{3}$ second^{-1}.

Legro et al. explain that for the power system assessment, the characterization of the surge formed within and propagating out of the regions via lines may be taking the form of a Norton equivalent source placed at the source region boundary, as shown in Figure 5-15.[14] Since the air conductivity within the region is high, Zs may be represented by a value of a few ohms. This implies that a surge on the line, which is incident to the region boundary from the exterior, will be reflected with some attenuation and propagate back into the grid. An alternate view is, because the air conductivity in the source region does not change abruptly at the boundary, an incident current surge, once penetrating the region, will perceive a variable line impedance due to the spatial difference in air conductivity. Such variable distributed loading of the line has been noted to minimize reflections in similar problems involving traveling waves on antennas. Thus, a reasonable selection for the source impedance Zs may be the characteristic line impedance (Zc).

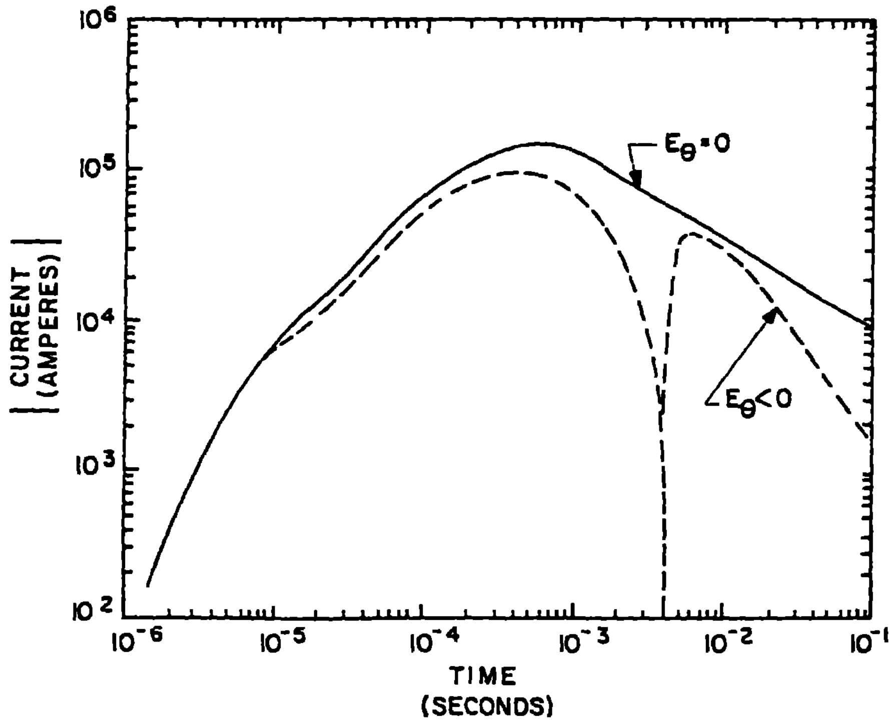
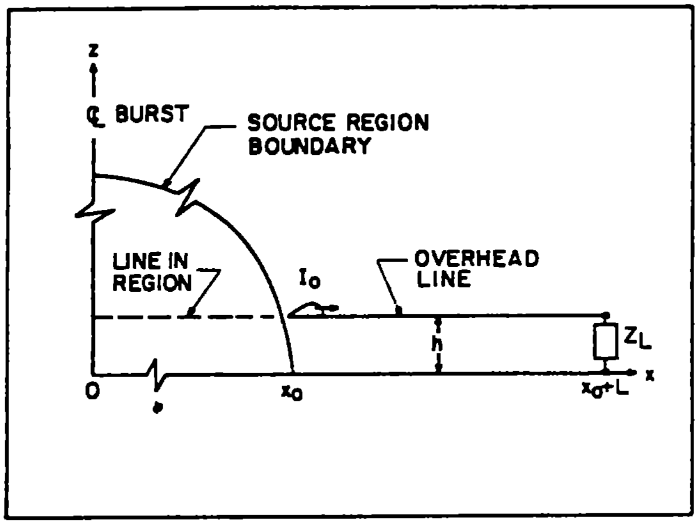
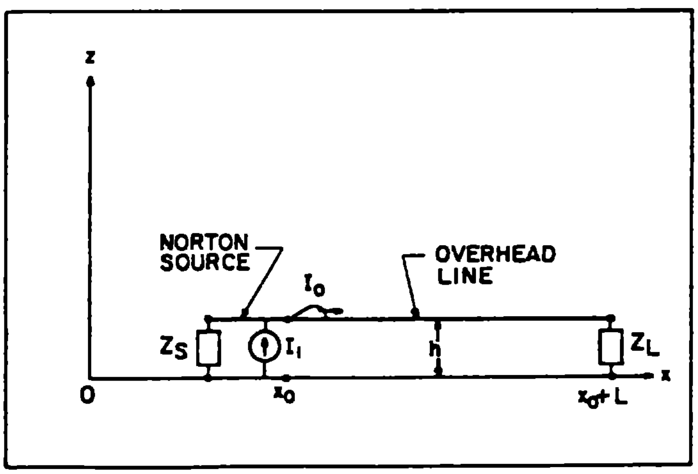


Figure 5-14. Graham calculation of the current into a 0.1-ohm load located at the end of a 2,300-meter-long overhead line in a nuclear surface burst source region.



a) Physical configuration.



b) Equivalent circuit.

Figure 5-15. Representation of the current surge formed within the source region on an overhead line by a Norton equivalent source located at the source region boundary.

Coupling Outside the Source Region

The radiated field outside the source region has a magnitude that decreases with increasing distances from the event. So the excitation of the power system by the field becomes weaker as a function of the distance. Outside the source region the excitation of the lines and cables is due to the tangential component of the electric field (Ex) along the line as well as by the vertical electric field (Ez) at both ends of the line.

Tesche et al. have developed a model to take into account the EMP effect in and outside the source region, as shown in Figure 5-16.[14]

ASSESSMENT METHODOLOGY

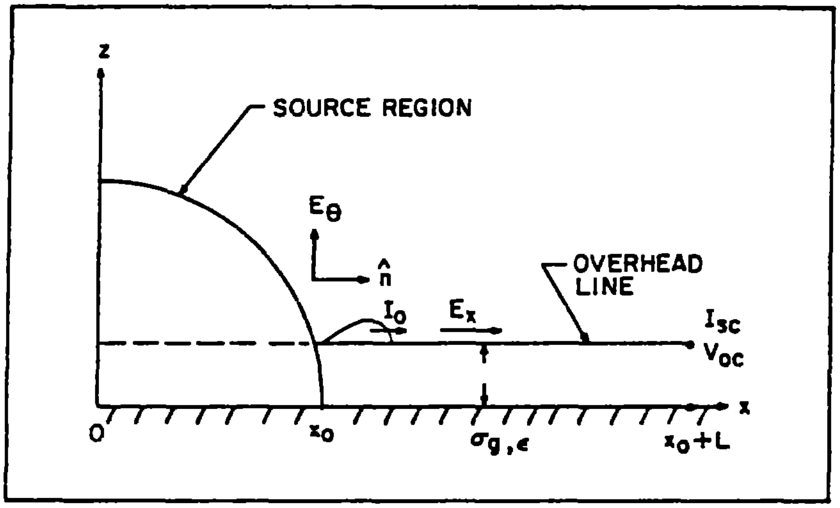
HEMP

Legro et al. assess the effects of detonation of a high altitude nuclear weapon from the time of the formation of a source region to two seconds after this formation. After two seconds the influence of the MHD EMP effects begins; it will be discussed later.

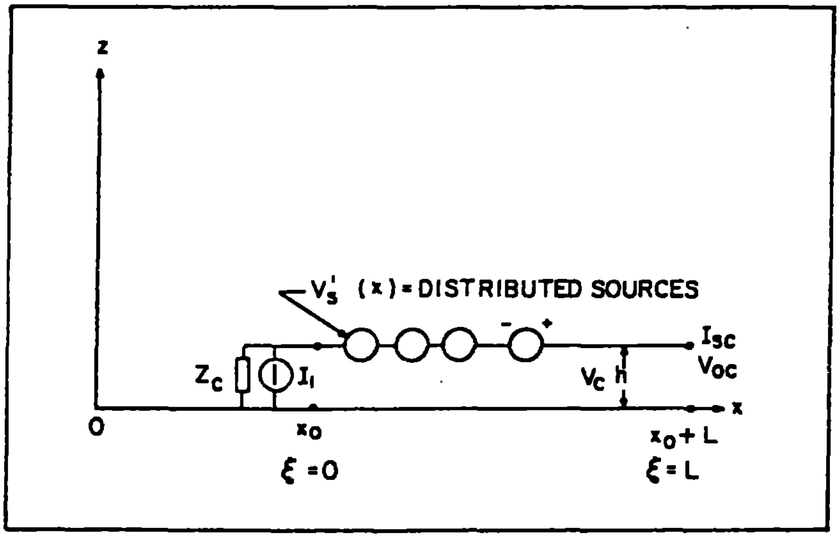
The power system network is that group of equipment that, taken together, generates, transmits, and delivers energy to its assigned customer load areas; the network includes communication and control necessary for the process. A representative utility network was presented in Figure 3-3, showing two major systems within the network--a power delivery system and a communication/control system. These two systems support the mission of the power network to control and deliver energy to certain geographically located customers through facilities at specific locations.

For the purposes of their methodology, Legro et al. consider this power delivery or communication/control system to be made up of a number of subsystems (Figure 5-17) that would be illuminated with the same HEMP field strength. These subsystems include generating plants, substations, power lines between substations, centers of control, and communication centers and communication links that are under the operation and control of a specific utility.

The equipment within a subsystem can be grouped according to the function performed. Each functional group of equipment may be assessed separately in many instances because, within the EMP illumination time, none of the functional groups can interact. Ultimately, however, their individual



a) Physical configuration.



b) Equivalent model circuit.

Figure 5-16. Physical geometry and electrical equivalent circuit for an overhead line excited by SREMP.

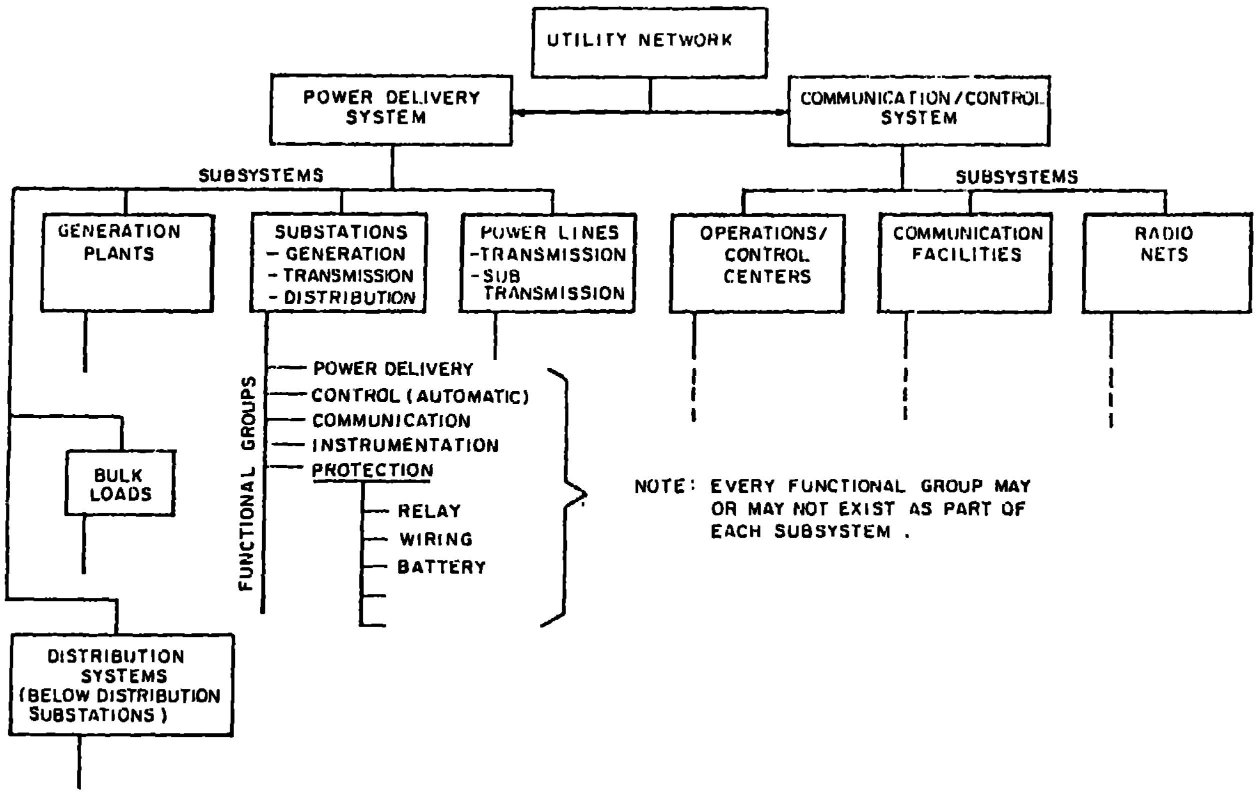


Figure 5-17. Hierarchy of elements of electric utility network.

viability or proper functioning can be affected by the functioning of the others, and must be taken into account.

The major functional groups are:

- Power delivery groups, such as in generation plants and substations, made up of generators (in the case of generation plants), power transformers, circuit breakers, and bus conductors.
- Protection, instrumentation, or control groups, such as overcurrent and overvoltage protective relays on transformers, capacitor banks, and power lines.
- Communications groups, such as transmitters and receivers, power line carrier systems, microwave systems, and telephone lines.

A transmission or power line is a special type of subsystem in that its major functional group is the power delivery group, made up simply of conductors. However, the phase conductors can serve as a circuit in a communications and protection functional group by providing the means of transmitting the signal for power-line carriers.

A functional group is made up of circuits and devices. For the purpose of this methodology, a circuit is a conductor or system of conductors through which an electric current is intended to flow, together with its associated shielding and splicing, etc. In this context, the communication link through air may be called the circuit of a communications functional group. A device is an assembly of components to serve a specific purpose such as, in the protection functional group, relays, current and/or potential transformers, battery supplies, switches, operating coils, and mechanisms on breakers. The device or circuit, defined in the IEEE standard dictionary of electrical and electronic terms, is the smallest entity considered by this methodology.

Figure 5-18 illustrates the elemental division of the utility network used in this methodology. The states of circuits and devices in a functional group determine the state of that functional group. The state of the functional group within the subsystem determines the state of the subsystem. The states of the subsystems within the power or communication/control system determine its state. Figure 5-19 provides an overview of the stages or levels of assessments.

One of the reasons for approaching the structure of the methodology in this manner is to allow different experts to assess major individual subsystems and/or circuits or devices within the functional group, or

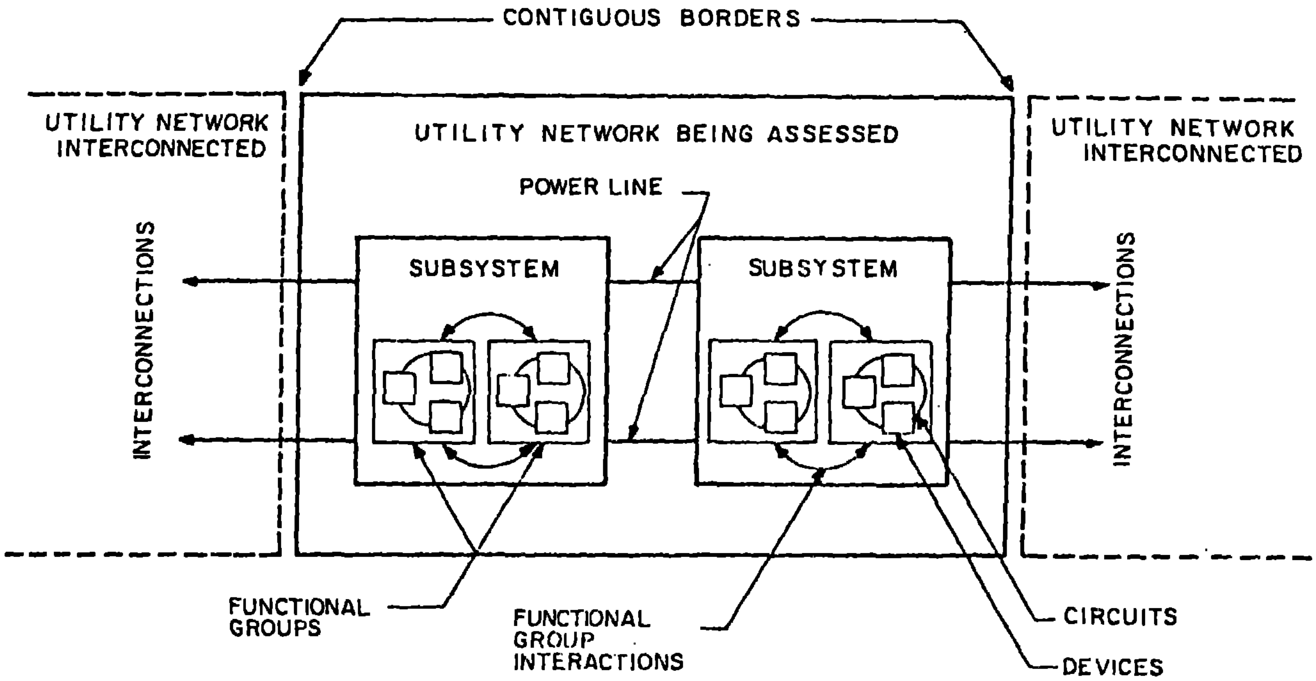


Figure 5-18. Elemental division of power system.

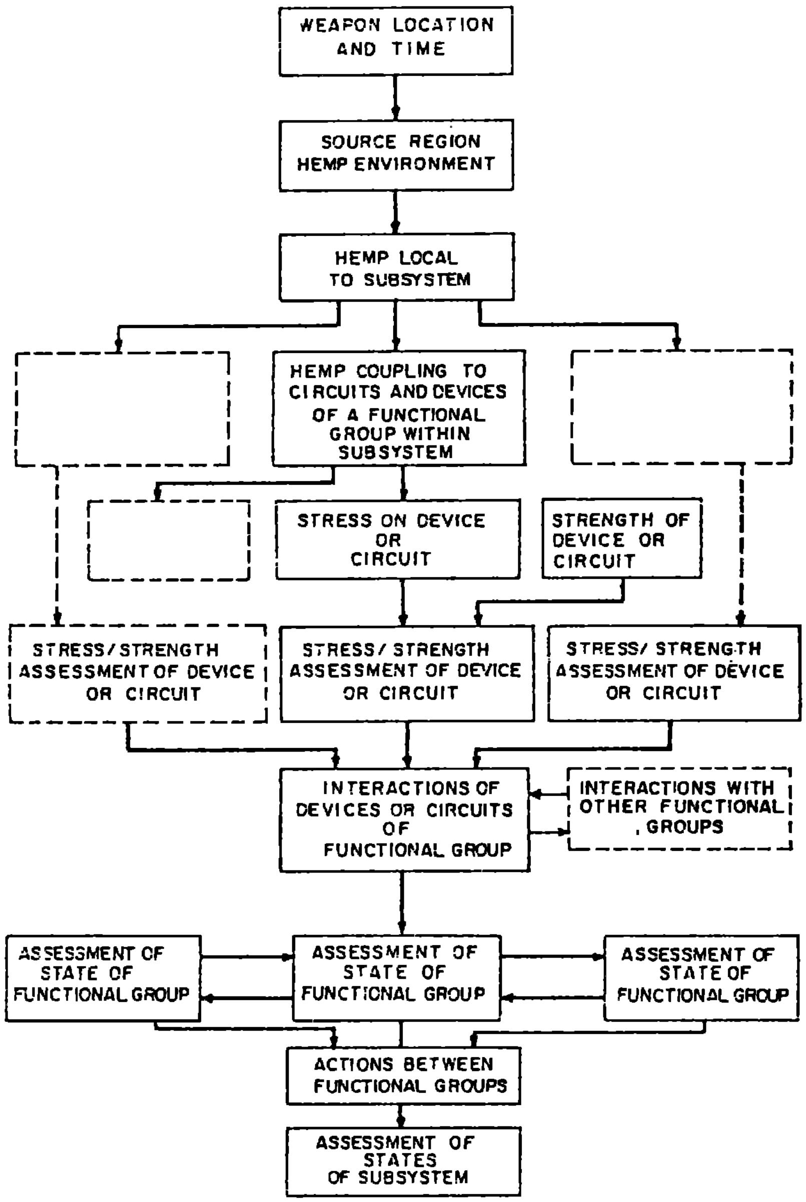


Figure 5-19. Flowchart and overview of assessment methodology to level of subsystem.

functional groups within a subsystem. The results of these individual assessments become part of the performance data base of the element being assessed.

Each functional group can be initially assessed separately from the others because failures and upsets of devices and circuits take place in a very short time within a group. By taking into account damage or upsets of individual devices and circuits, fault trees of failures and upset of the functional group may be developed with the objective of identifying the potential for the total functional group failing.

The assessment of the states of a given subsystem is shown in Figure 5-19. The top three blocks define the HEMP environment (fields to the local HEMP in which the subsystem and its functional group lie). This local environment, using models and codes for coupling to individual circuits and devices, is used to determine the stress (voltage, current, or energy) produced in these circuits and devices within the functional group by the HEMP local wave. The stress on a particular circuit or device is compared through its stress/strength models to the strength of the device (or circuit). Available data on such strengths are used; where stress models or data bases are not available, calculations and engineering evaluations are made, or experiments performed, to supply this information. Similar assessments are performed for other devices and circuits making up the functional group. Through interaction sequence, fault trees, or connection diagrams of such failures within the functional group, an assessment is made to determine the effects of the failures on changes of state of the functional group.

At the next stage of the analysis, the assessed change in states of the functional groups of a subsystem are used to assess the change in state of the subsystem. The change of states of all subsystems are then assessed individually to determine the effects on the initial change of state within the complete power system network (Figure 5-20).

MHD EMP

Legro et al. provide an overview of the MHD EMP assessment methodology, which is diagramed in Figure 5-21.[13] For a single high altitude nuclear burst, the MHD EMP environment will always be preceded by a HEMP environment. The system under investigation will sense and react to the existence of HEMP, but many of the transient operations occurring within this change of

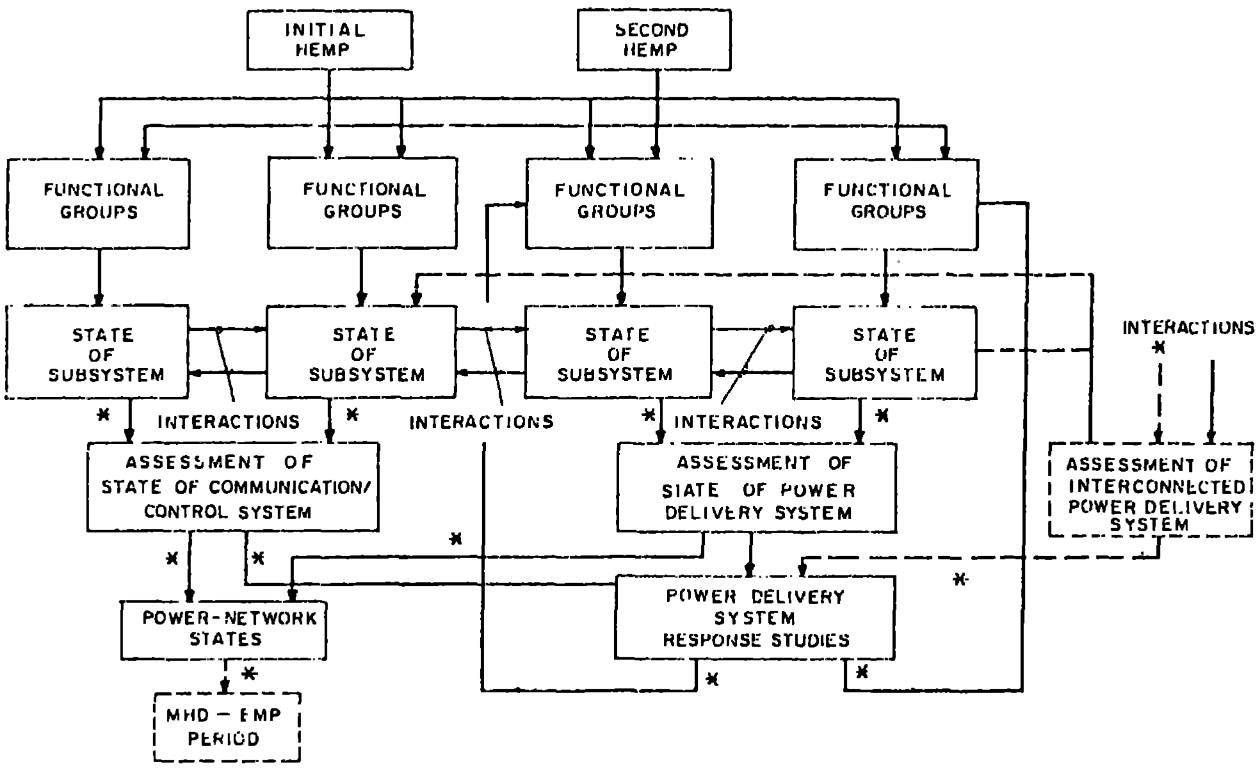


Figure 5-20. Flowchart of power network assessment.

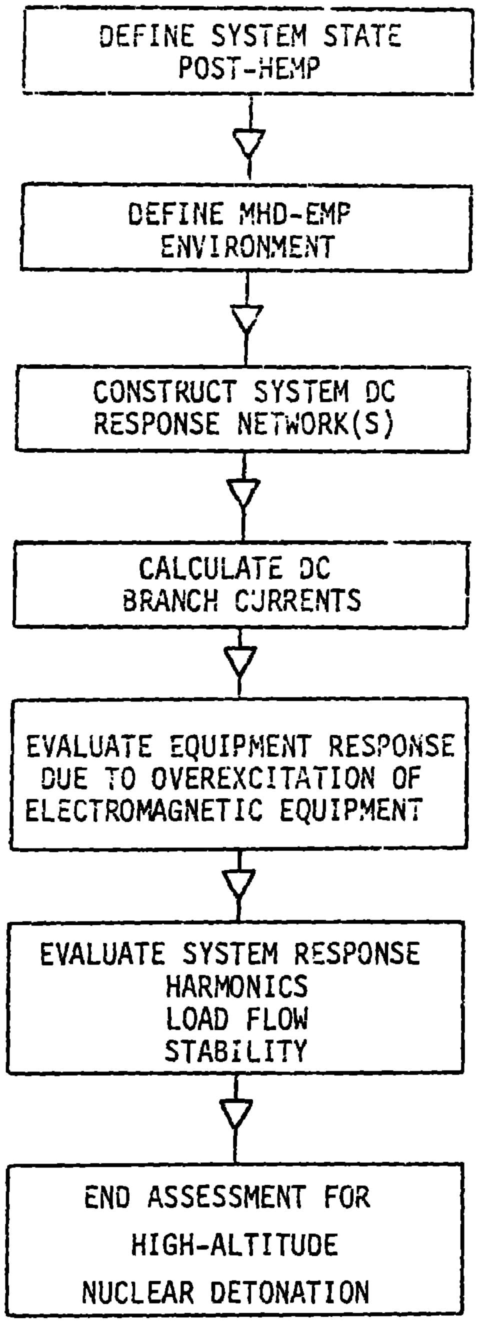


Figure 5-21. Overview of MHD EMP assessment methodology.

"state" will eventually be completed within an elapsed time of seconds. The power system can be considered to be in a new "state," which serves as one set of initial conditions for MHD EMP assessment.

At the end of the process, it will be possible to know the state of the electrical power system after the analysis of the load flow and stability.

SREMP

The methodology acknowledges three distinct transient environments produced by the nuclear surface burst.[14] In terms of spatial coverage, the smallest of these environments is the source region. The threats for evaluation are transient electrical surges formed on lines exciting this region. These surges propagate away from the boundary into the grid prior to physical damage to the line. The threats of interest are: 1) consequential damage to equipment and facilities beyond the source/physical damage region proximate to the burst and 2) system instability caused by the system's protective reaction to such surges.

The second environment, also spatially local in area, is the region of initial direct damage. The methodology incorporates this threat by acknowledging: 1) the time progressive destruction of the power system in this area, 2) the relevant loss of generation and/or load, and 3) the system's protective reaction to isolate this damaged portion of the grid from the rest of the system.

The third transient environment, which is spatially greatest in terms of the nuclear surface burst, is that portion of the system illuminated by the radiated (free) fields outside the source region. The questions and concerns associated with this phenomenon are methodologically quite similar to those associated with HEMP investigation.

Preliminary analysis of the nature of these three environments strongly suggests that the order of assessment proceed as follows:

- Investigate SREMP radiated (free) field interaction with the grid.
- Evaluate the consequences of surge propagation on lines intersecting the source region boundary.
- Incorporate non-EMP physical damage in time sequences of events.

An overview of the progression is shown in Figure 5-22. Recursive power system load flow/stability simulations are incorporated to investigate the magnitude and extent of system disturbances.

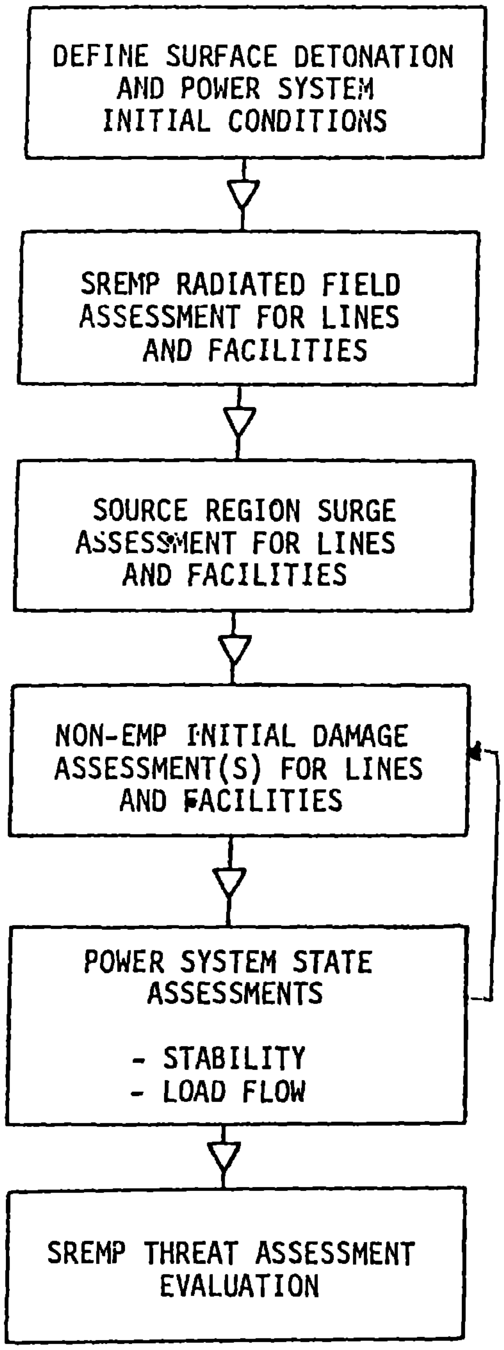


Figure 5-22. Overview of methodology for SREMP assessment for civilian electric utility systems.

In contrast to transient EMP environments created by high altitude nuclear events that can directly excite vast areas of the national power system, EMP environments associated with surface nuclear events are local in extent. A spatial shift of a few kilometers in the assumed location of the burst may result in significantly different assessments for otherwise identical scenarios.

At the conclusion of the source region surge analysis, the real time of the system is several milliseconds after the burst. The system state at the time is based on: 1) estimates of EMP damage/misoperation and 2) fault conditions requiring system protective operation. In addition, the methodology now acknowledges the non-EMP damage associated with the surface burst. For the purpose of this methodology, such damage may be divided into two areas, one established by the fireball radial distance plus an outer perimeter established by peak overpressure. Systemic damage to the power grid out to the fireball radius is added to the post EMP systems state to form the input data simulation case for a transient stability study. An overview of this procedure is shown in Figure 5-23.

PROTECTION

There are two different approaches to protecting systems from the effects of the EMP.[18] The first one, which is used for most high priority military systems, is based on the premise that these systems are so electromagnetically complex that it is not possible to determine with high confidence the response of the system to a large amplitude, fast transient such as the EMP. Hence, the reasoning goes that the systems must be isolated from EMP so that their components are not overstressed by the EMP. The system is overstressed if it is more highly stressed by the EMP than by the normal peacetime environment.

The other approach, called "tailored hardening," stipulates that most of the systems will already tolerate the EMP. The hardening task is thus to identify the weak points in the system and provide sufficient protection so that they too will tolerate the EMP. It is usually argued that this tailored approach offers more economical EMP protection than the high confidence approach, previously described, in which "everything is protected whether it needs it or not." This is not usually recommended for high priority systems, however, because it is difficult to be certain that all of the weak spots have

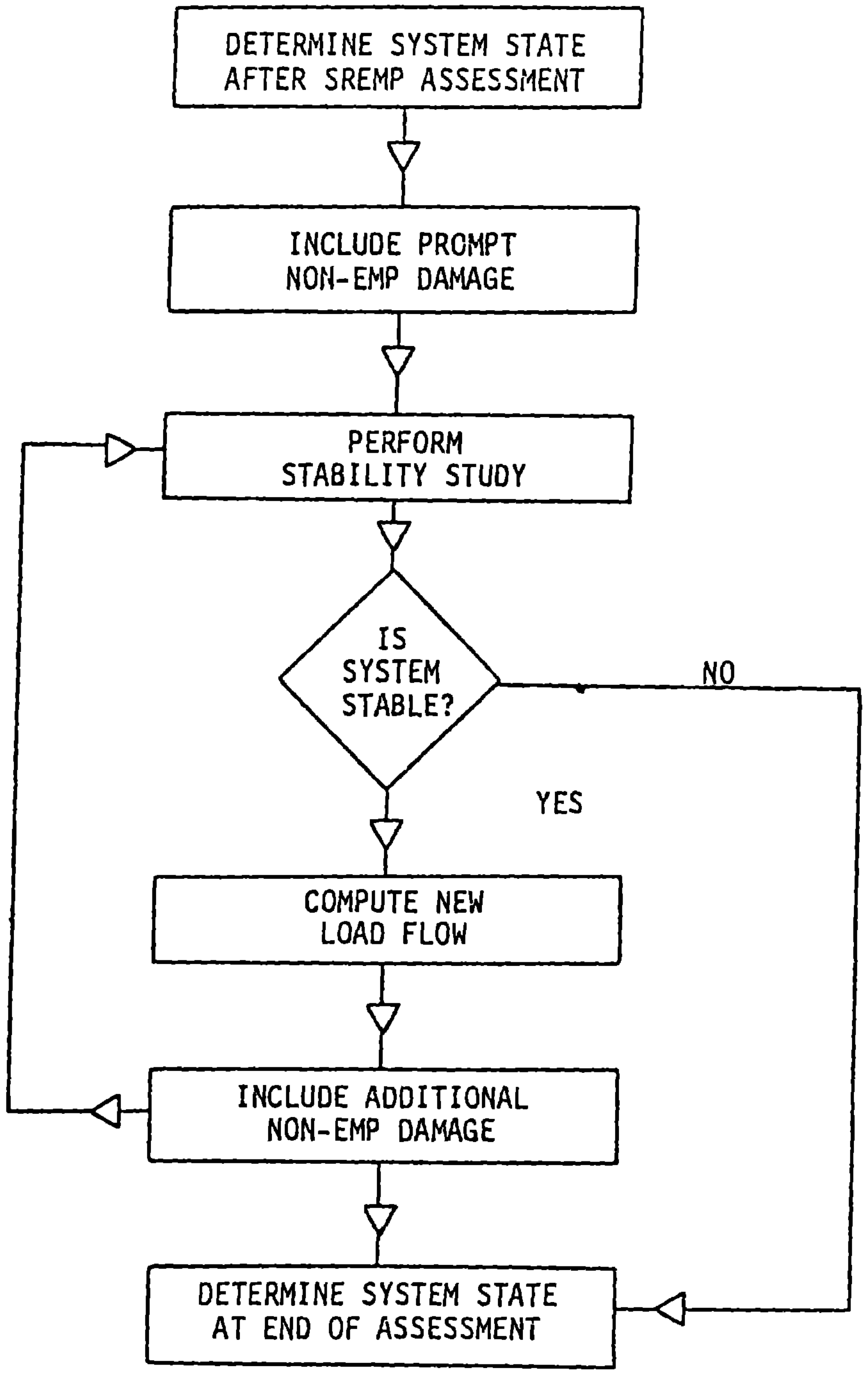


Figure 5-23. Overview of system stability assessment methodology.

been identified when the source is the short duration, high amplitude EMP, and the responses may involve non-linearities such as arcing.

For very simple systems or components, the tailored hardening approach may be useful if a combination of high level testing and analysis is used to locate the weaknesses. Thus for transmission and distribution transformers, and perhaps for other transmission line components, this appears to be practical. However, for the complex portions of electrical power systems, too many circuit states and modes of excitation have to be understood under high amplitude, fast transient excitation to have much confidence that all the weak spots can be identified and fixed. In these segments of the system, the use of a closed electromagnetic barrier to isolate the complex parts of a shield and the necessary filters, surge limiters, and aperture treatment are recommended.

Protection of electronic circuits against the EMP is important because these circuits often control large quantities of power with fairly small digital signals. Hence, a small transient that is misread by the digital circuit can cause large scale changes in the system. Protection is achieved by creating an electromagnetic barrier; essential wire penetrations must be closed with surge limiters, filters, and common-mode rejection devices. Groundable conductors such as pipes, conduits, waveguides, and cable shields can be perfectly bonded to the shield so that internally induced currents do not flow inside the shield. The apertures must be minimized to limit the EMP penetration.

It is postulated that power transmission and distribution components may be made immune to the effects of EMP by increasing their dielectric strength or by providing surge arresters to limit the high voltage stresses on the insulation. Indirect effects triggered by the EMP might be prevented or limited by instigating procedures that prevent or limit the propagation of the EMP effects through the system.

Many of the important components of generation plants are located inside plant buildings that are often constructed with reinforced concrete or a metal exterior. Metal and reinforced concrete buildings with appropriate grounding and aperture treatments can serve as the first electromagnetic barrier for EMP protection. A combination of electromagnetic barriers at the building level and at the system level, and surge suppression techniques on cable entering the building may have to be employed to reduce the EMP stress to an acceptable level (a level below that of the normal operational stresses).

If sufficient warning time is available, special control and operational procedures may be used to mitigate some EMP effects. A previous study concluded that 50% of the distribution substation transformers could be isolated within a 45-minute warning period. Other special control actions might consist of breaking up large interconnections into islands to avoid the propagation of instability.

6. CONCLUSIONS

The electric power system is a large and complex set of networks and subsystems. The technology employed is diverse, ranging from relatively unsophisticated high power technology to that with more sophisticated electronic components.

The study of the vulnerability of this system to the effects of nuclear electromagnetic pulse shows the difficulty and the high complexity of the problem. A broad range of expertise in power systems technology and nuclear effects is required to achieve the goal. The DOE program, partly described in this paper, is planned until 1989. The determination of the vulnerability of the existing power system and the recommendations and development of new technologies to decrease it, which are the purpose of this program, will permit the next step, which is the implementation of these technologies. Even though the cost of the current program is about two or three million dollars each year, the implementation could reach a billion dollars or more each year to achieve a substantial improvement in the whole system.

In Europe, several countries are now involved in studying the vulnerability of their own electrical power systems. Scientists from these countries would welcome the opportunity to discuss their results with their American counterparts in charge of the DOE program. Although most of the procedures could be shared and discussed, some of the European electrical power systems need specific research and effort. Understanding the effects of EMP on nuclear power systems is of major interest to these countries (for example, Sweden, Belgium, and France), because they rely on nuclear energy to a far greater extent than does the United States.*

*TIME, May 12, 1986, Percentage of toal electricity generated by nuclear energy: U.S.A. 17%, Sweden 50%, Belgium 60%, France 65%.

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APPENDIX A

DOE/NBB-033 PROGRAM OBJECTIVES

The DOE/EES EMP program is designed to develop technologies and systems to enable electric power systems to: 1) provide power to essential loads such as military installations, civil defense facilities, and critical industries; 2) reduce damage to the overall power system; and 3) minimize power outage time to the public. The development of a systematic approach to accomplish these three goals is the objective of this program. The specific objectives are:

1. to develop scientific and mathematical models for representing the influence of EMP on electric power systems;

2. to develop analytical methods for assessing the effects of EMP on electric power systems;

3. to develop a data base from simulation studies and experiments for characterizing power system response to EMP;

4. to develop and evaluate measures designed to minimize the influence of EMP on electric power systems; and

5. to provide information and recommendations for electric power structural and operational requirements when subjected to EMP disturbances.

The technologies and systems that will be developed to achieve the program objectives include analytical and modeling techniques, assessment methodologies, protection hardware, and special operating and control strategies. Recommendations for protecting electric power systems against EMP will result from this research program; however, the implementation of EMP protection and contingency strategies is not included as part of this program.

APPENDIX B

DOE/NBB-033 PROGRAM PLAN

Five major elements of activity comprise the DOE/ESS EMP research and development program:

- Element 1 (E1)--EMP surge characterization and effects;
- Element 2 (E2)--development and testing of a comprehensive EMP assessment methodology for electric power systems;
- Element 3 (E2)--development of strategies for operation and control of electric power systems under the influence of EMP;
- Element 4 (E2)--definition, development, and testing of requirements for hardware under the influence of EMP; and
- Element 5 (E2)--evaluation of EMP impacts on new generation and control technology for electric power systems.

The relationship between the specific objectives and the program elements is shown in Figure B-1. Figure B-2 shows the time sequence of the five program elements through FY88. Information on EMP-induced surges and the effects of EMP surges on power system components resulting from studies conducted under Element 1 will be used in the asessment task (Element 2) and the hardware requirements task (Element 4). Information provided by the assessment methodology and testing task (Element 2) will be used in studies on operations and control (Element 3). All five program elements will provide information, technology, and systems needed to develop recommendations for minimizing the effects of EMP on power systems.

The following discussion briefly reviews each of the individual program elements.

ELEMENT 1: EMP SURGE CHARACTERIZATION AND EFFECTS

A description of the surges induced in electric power system transmission and distribution lines and the effects of these surges on system components is necessary to analyze the impact of EMP on electric power systems. Techniques to compute the EMP energy and induced transients coupled to antennas, shielded cables, phone lines, cables within partially shielded enclosures, etc., have been developed by Department of Defense (DOD) programs. These techniques will be useful to assessing the impact of EMP on electric power system controls and

Specific Objectives	E1	E2	E3	E4	D5
Development of models for analysis	●	●	●		
Development of analytical methods for assessing the effects of EMP on power systems		●			
Development of a data base for characterizing power system response to EMP	●	●	●		
Development and evaluation of measures to protect power systems against EMP	●		●	●	●
Development of recommendations for EMP protection and contingency planning	●	●	●	●	●

Figure B-1. Specific program objectives and elements.

Elements	FY83	FY84	FY85	FY86	FY87	FY88
E1: EMP surge characterization and effects	XXXX	XXXXXXXX	XXXXXXXX	XXXXXX		
E2: EMP assessment methodology development and testing	X	XXXXXXXX	XXXXXXXX	XXXXXXXX	XXXX	
E3: Operation and control		XXXX	XXXXXXXX	XXXXXXXX	XXXXXXXX	
E4: Definition, development, and testing of hardware requirements			XX	XXXXXXXX	XXXXXXXX	XXXXXX
E5: EMP impact on new generation and control technology			XXXX	XXXXXXXX	XXXXXXXX	XXXXXX

Figure B-2. EMP program overview

military facilities have been studied in DOD programs, much work remains to characterize fully the surges induced by EMP in transmission and distribution systems and to determine the impact on transmission and distribution components.

Element 1 will fill the information gap between that required for this program and the results from DOD research programs. The impact of multiple lines, corona, and the system network on the induced surges will be investigated. The impact of fast-rising surges on components will also be studied. The sub-elements of Element 1 are given in the following chart.

E1.1: EMP Interaction and Coupling to Exposed Lines--This task characterizes the surges induced in single-phase and three-phase transmission and distribution lines by EMP. The effects of corona will be taken into account.

E1.2: EMP Transient Network Analysis--A theoretical model for the analysis of EMP-induced transients in a large power system network will be developed in this task. The model will include nonlinear effects of flashover and arresters. A representative power system grid will be used to test the model.

E1.3: Component Response and Model Validation Texts--The response of power system components such as transformers, capacitor banks, arresters, etc. to EMP surges will be determined experimentally under this task. The threshold levels for damage of a selected number of components will also be determined. The models used in Tasks E1.1 and E1.2 will be experimentally validated as necessary. A theoretical model for the analysis of insulation failure to fast-rising, short-duration, EMP-induced surges will be developed and tested in this task. Insulation failures include insulation puncture with or without partial healing and insulator flashover.

The schedule and interrelationship of the sub-elements are shown in Figure B-3.

Sub-elements	FY83	FY84	FY85	FY86	FY87	FY88
E1.1: EMP Interaction and Coupling to Exposed Lines	xxxx	xxxxxxxx	xxxx			
E1.2: EMP Transient Network Analysis	xx	xxxxxxxx	xxxxxxxx			
E1.3: Component Response and Model Validation Texts		x	xxxxxxxx	xxxx		

Figure B-3. Schedule for EMP surge characterization and effects (E1).

ELEMENT 2: DEVELOPMENT AND TESTING OF A COMPREHENSIVE EMP ASSESSMENT METHODOLOGY FOR ELECTRIC POWER SYSTEMS

At present, no comprehensive methodology exists for assessing the effects of EMP on electric power systems. Available assessment techniques have been developed to evaluate effects on facilities and military systems. These techniques, while applicable to portions of electric power systems, will have to be developed further to account for the impact of system operations and control and the failure mechanisms associated with high-voltage power circuits. The sub-elements of Element 2 are given in the following chart.

E2.1: <u>EMP Assessment Methodology Development</u>--This task will develop an EMP methodology to determine the effects of EMP on power system components, subsystems, and operation. This study will determine the likelihood of components or subsystem damages or malfunction and the subsequent impact on the overall response of the power system. This task will necessarily include the effects of EMP on transmission and distribution systems, communications and control systems, generation, and loads. Operation and control strategies will be included in this study to determine the overall behavior of power systems under the influence of EMP.

E2.2: <u>Assessment of EMP Effects on Electric Power Systems</u>--This task will determine the response of representative electric power systems to EMP by the application of the methodologies developed under sub-element E2.3. It will analyze the ability of electric power systems to function after possible EMP impacts such as islanding, damages to automatic control systems and communication systems, and malfunctions in generation, transmission, and distribution systems. The time to recover from one or more EMP events will be estimated as part of this study.

The schedule and interrelationships of the sub-elements in Element 2 are shown in Figure B-4.

Sub-elements	FY83	FY84	FY85	FY86	FY87	FY88
E2.1: EMP assessment methodology development	xx	xxxxxxxxx	xx			
E2.2: Assessment of EMP effects		xxxxx	xxxxxxxx	xxxxxxxx	xxxx	

Figure B-4. Schedule for EMP assessment methodology development and testing (E2).

ELEMENT 3: DEVELOPMENT OF STRATEGIES FOR OPERATION AND CONTROL OF ELECTRIC POWER SYSTEMS UNDER THE INFLUENCE OF EMP

This element of the EMP program is designed to investigate operation and control strategies for mitigating the effects of EMP on electric power systems. These strategies range from advanced emergency-state control to special actions and procedures initiated upon warning that an EMP event may be forthcoming.

The results of this program element will be useful to the appropriate agencies and committees responsible for contingency planning. An important consideration is the impact of these strategies on the social and economic well-being of the nation. Therefore, a socioeconomic analysis is included in this work. The sub-elements of Element 3 are given in the following chart.

E3.1: <u>Emergency-State Control for Major Disturbances</u>--This study will investigate emergency-state control measures for numerous and large disturbances distributed throughout the electric power system.

E3.2: <u>Operating and Control Strategies for Mitigation of EMP Effects</u>--This task will investigate operating and control strategies for electric power systems under the influence of EMP. These strategies will include necessary control procedures for major disturbances as well as special procedures and system configurations to mitigate the effects of EMP. Particular focus will be placed upon restoration techniques.

E3.3: <u>Socioeconomic Impact of EMP and Special Operating and Control Strategies</u>--The socioeconomic impacts of present and proposed operating and control strategies are an important consideration in contingency planning. This study will evaluate the social and economic impacts of operating and control strategies proposed to mitigate EMP effects.

E3.4: <u>Testing and Evaluation of Operating and Control Strategies</u>--This study will analyze the effectiveness of special operating and control strategies with acceptable socioeconomic consequences. The special operating and control strategies will be used in EMP assessments of representative electric power systems. The effectiveness of the strategies for mitigation of EMP effects will be determined. Operating and control strategies that provide protection to electric power systems against EMP will be identified.

The schedule and interrelationship of the sub-elements are shown in Figure B-5.

Sub-elements	FY83	FY84	FY85	FY86	FY87	FY88
E3.1: Emergency-state control for major disturbances			xxxxxxxx	xxxx		
E3.2: Operation and control strategies				xxxxxx	xxxxxxxx	
E3.3: Socioeconomic studies		xxxx	xxxxxxxx	xxxxxxxx	xx	
E3.4: Testing and evaluation strategies				xxxx	xxxxxxxx	

Figure B-5. Schedule for development of strategies for operation and control of electric power systems under the influence of EMP (E3).

ELEMENT 4: DEFINITION, DEVELOPMENT, AND TESTING OF REQUIREMENTS FOR HARDWARE UNDER THE INFLUENCE OF EMP

New hardware may be required to protect electric power systems under the influence of EMP. EMP hardware requirements will be coordinated with lightning and electromagnetic compatability requirements as appropriate. Protection hardware may range from modifications of present state-of-the-art hardware to new materials and techniques. The sub-elements of Element 4 are given in the following chart.

E4.1: Definition and Development--This task will define EMP and/or EMP/lightning specification and testing requirements for hardware used in electric power systems. The requirements defined by this study will be used to develop data and concepts for EMP/lightning power systems haredware, including protection hardware. This task will also develop hardware to meet the EMP/lightning specifications. This effort may range from the development of new materials with appropriate insulating properties or surge suppression performance to combining state-of-the-art arrester and filter techniques with existing hardware.

E4.2: Hardware Tests--Electric power system hardware will be experimentally tested to determine if EMP/lightning specifications are met under this sub-element. The hardware to be tested will include both existing power systems hardware and newly developed hardware.

E4.3: Hardware Recommendations--This study will develop hardware recommendations required to protect electric power systems against EMP in order to 1) provide power to critical loads, 2) minimize damage to electrical equipment, and 3) minimize power outage time to the public.

The schedule of the sub-elements of Element 4 are shown in Figure B-6.

Sub-elements	FY83	FY84	FY85	FY86	FY87	FY88
E4:1 Definition and development of requirements for hardware			xx	xxxxxxxx	xxxxxxxx	xxxxxxx
E4:2 Hardware tests				xxx	xxxxxxxx	xxxxxxx
E4:3 Hardware recommendations					xxx	xxxxxxx

Figure B-6. Schedule for definition, development, and testing of hardware requirements under the influence of EMP (E4).

ELEMENT 5: EVALUATION OF EMP IMPACTS ON NEW GENERATION AND CONTROL TECHNOLOGY FOR ELECTRIC POWER SYSTEMS

As the penetration of new technologies into electric power systems proceeds, the effects of EMP on these technologies could have a significant impact on the overall power system. This element aims at determining the EMP effects on new generation and control technology being developed and integrated into electric power systems. Also, this element will determine EMP hardening requirements and specifications for new generation and control technologies. The objective of this element is to develop EMP specifications and hardening techniques that can be used in the design of new technologies and EMP test standards that can be used to ensure that the new technologies meet EMP specifications. The sub-elements of Element 5 are given in the following chart.

E5.1: EMP Effects on New Generation Technologies for Electric Power Systems--This task involves an assessment of EMP effects and hardening requirements for new generation technologies being integrated into electric power systems in the near future. Such technologies include photovoltaic arrays, solar power tower generators, wind turbine arrays, small hydrogenerators, geothermal power plants, etc. Advanced nuclear generation technologies will be addressed when such power sources are identified as plausible technologies.

E5.2: EMP Effects on Distribution Automation and Control (DAC) and Load Control Systems--This task will assess the EMP effects and hardening requirements for distribution automation and control systems being developed for electric power systems.

E5.3: Component Specifications for New Development for Electric Power Systems--This task will develop EMP specifications for new developments that will impact electric power systems. The new developments designed to meet EMP specifications will ensure that such technologies will not increase vulnerability of electric power systems to EMP.

The schedule and interrelationships of the sub-elements of Element 5 are shown in Figure B-7.

Sub-elements	FY83	FY84	FY85	FY86	FY87	FY88
E5:1: EMP effects on new generation technologies			xx	xxxxxxxx	xxxxxxx	xxxxxxx
E5.2: EMP effects on DAC			xx	xxxxxxxx	xxxxxxx	xxxxxxx
E5.3: EMP specifications for new developments						xxxxxxx

Figure B-7. Schedule for evaluation of EMP impacts on new generation and control technology for electric power systems (E5).

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